AFRL-RQ-WP-TM-2013-0264

SPATIALLY TARGETED ACTIVATION OF A SHAPE MEMORY POLYMER-BASED RECONFIGURABLE SKIN SYSTEM

Greg Reich, James Joo, and Nate DeLeon

Design and Analysis Branch
Aerospace Vehicles Division

Richard Beblo and John Puttmann

University of Dayton Research Institute

DECEMEBER 2013
Interim Report

Approved for public release; distribution unlimited.
See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
AEROSPACE SYSTEMS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the USAF 88th Air Base Wing (88 ABW) Public Affairs Office (PAO) and is available to the general public, including foreign nationals.

Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RQ-WP-TM-2013-0264 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

*//Signature//

JAMES J. JOO
Program Manager
Design and Analysis Branch
Aerospace Vehicles Division

//Signature//

THOMAS C. CO, Chief
Design and Analysis Branch
Aerospace Vehicles Division

//Signature//

CARL TILMANN, Principal Scientist
Aerospace Vehicles Division
Aerospace Systems Directorate

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

*Disseminated copies will show "//Signature//" stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
December 2013	Interim	01 October 2012 – 30 September 2013

4. TITLE AND SUBTITLE
SPATIALLY TARGETED ACTIVATION OF A SHAPE MEMORY POLYMER-BASED RECONFIGURABLE SKIN SYSTEM

5a. CONTRACT NUMBER In-house
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 62201F

6. AUTHOR(S)
Greg Reich, James Joo, and Nate DeLeon (AFRL/RQVC)
Richard Beblo and John Puttmann (University of Dayton Research Institute)

5d. PROJECT NUMBER 2401
5e. TASK NUMBER
5f. WORK UNIT NUMBER Q0Q0

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Design and Analysis Branch (AFRL/RQVC)
Aerospace Vehicles Division
Air Force Research Laboratory, Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7542
Air Force Materiel Command, United States Air Force

University of Dayton
Research Institute
300 College Park
Dayton, OH 45469

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RQ-WP-TM-2013-0264

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7542
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RQVC

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RQ-WP-TM-2013-0264

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PA Case Number: 88ABW-2013-3534; Clearance Date: 08 Aug 2013. Report contains color.
This document is comprised wholly of a slide show presentation.

14. ABSTRACT
The objective of the project is to investigate the thermomechanical behavior of engineered shape memory polymer (SMP) materials for use as composite reconfigurable skin systems in morphing aircraft applications. An anisotropic, reconfigurable skin based on selective heating of a cellular SMP material will be designed and investigated to understand its material characteristics.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			James J. Joo
Unclassified	Unclassified	Unclassified	SAR	40	**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

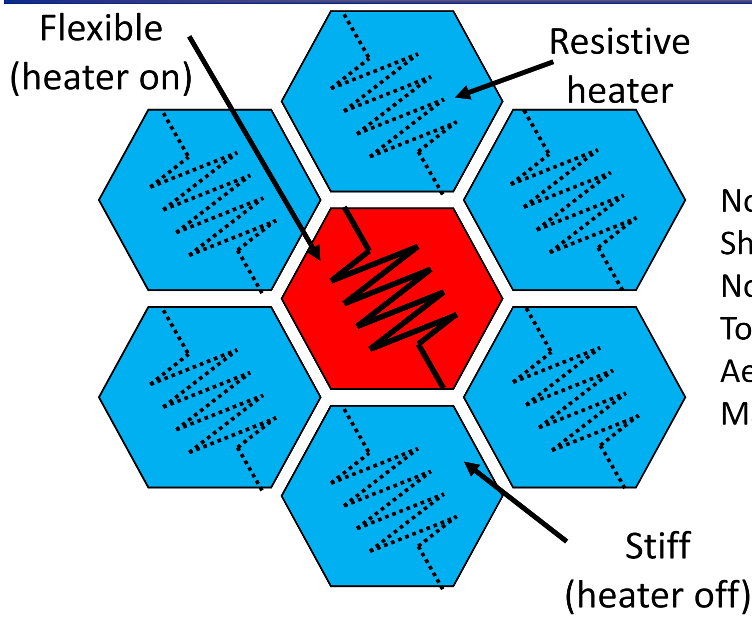
Spatially Targeted Activation of a Shape Memory Polymer Based Reconfigurable Skin System

Dr. Greg Reich
Dr. James Joo
Capt Nate DeLeon
Aerospace Systems Directorate
Dr. Richard Beblo
Mr. John Puttmann
UDRI

Outline

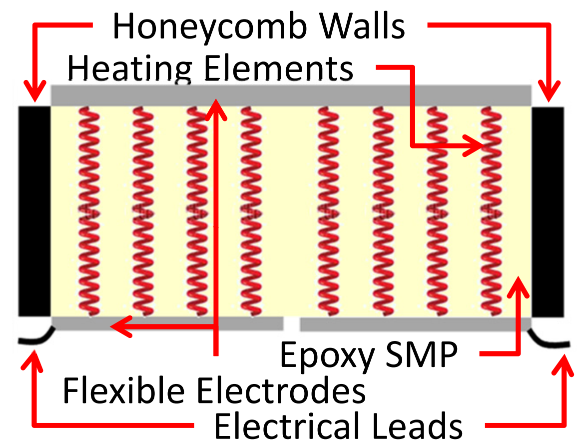
- Project Outline
- Project Roadmap
- Magnetic and Thermal Modeling
- Heating Scheme Proof of Concept
- Epoxy SMP Characterization
- Composite Analytic Model
- Composite Characterization
- Composite FEA Model
- System Modeling
- Honeycomb Geometry Optimization
- Heating Pattern Optimization
- Future Work
- Conclusions

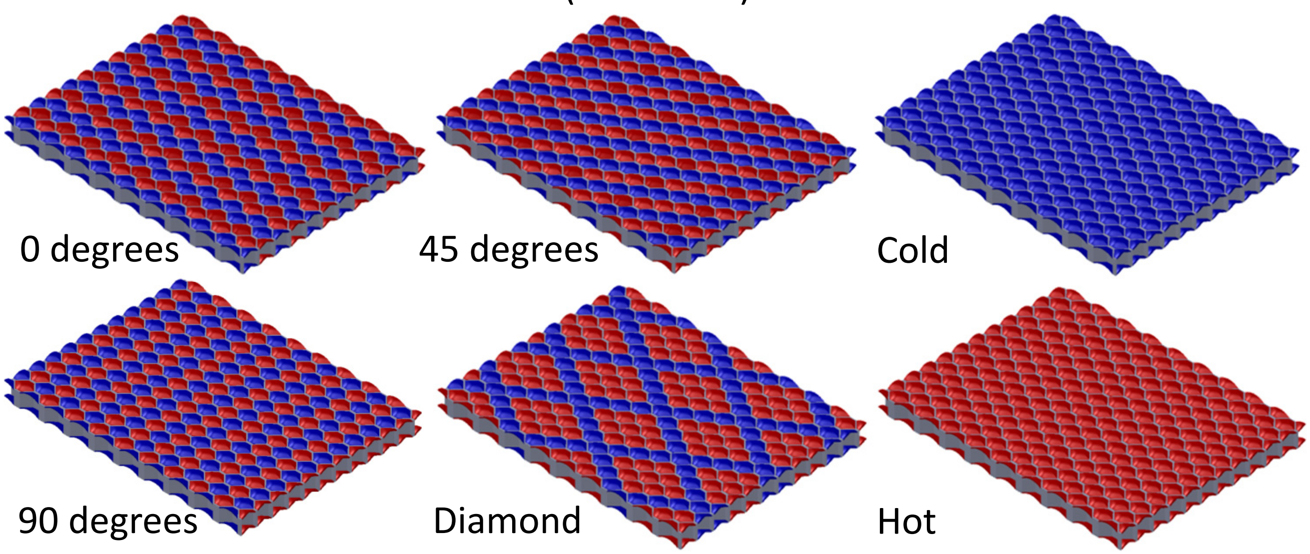
Project Outline



Skin Objectives (via MAS)

Nominal Panel Size 15” x 20”
Shear from 30° to 75°
No Wrinkling of Skin
Total Skin Weight <0.95 lb/sqft
Aerodynamic Load 400lb/sqft
Max Out-of-Plane Deflection 0.1”



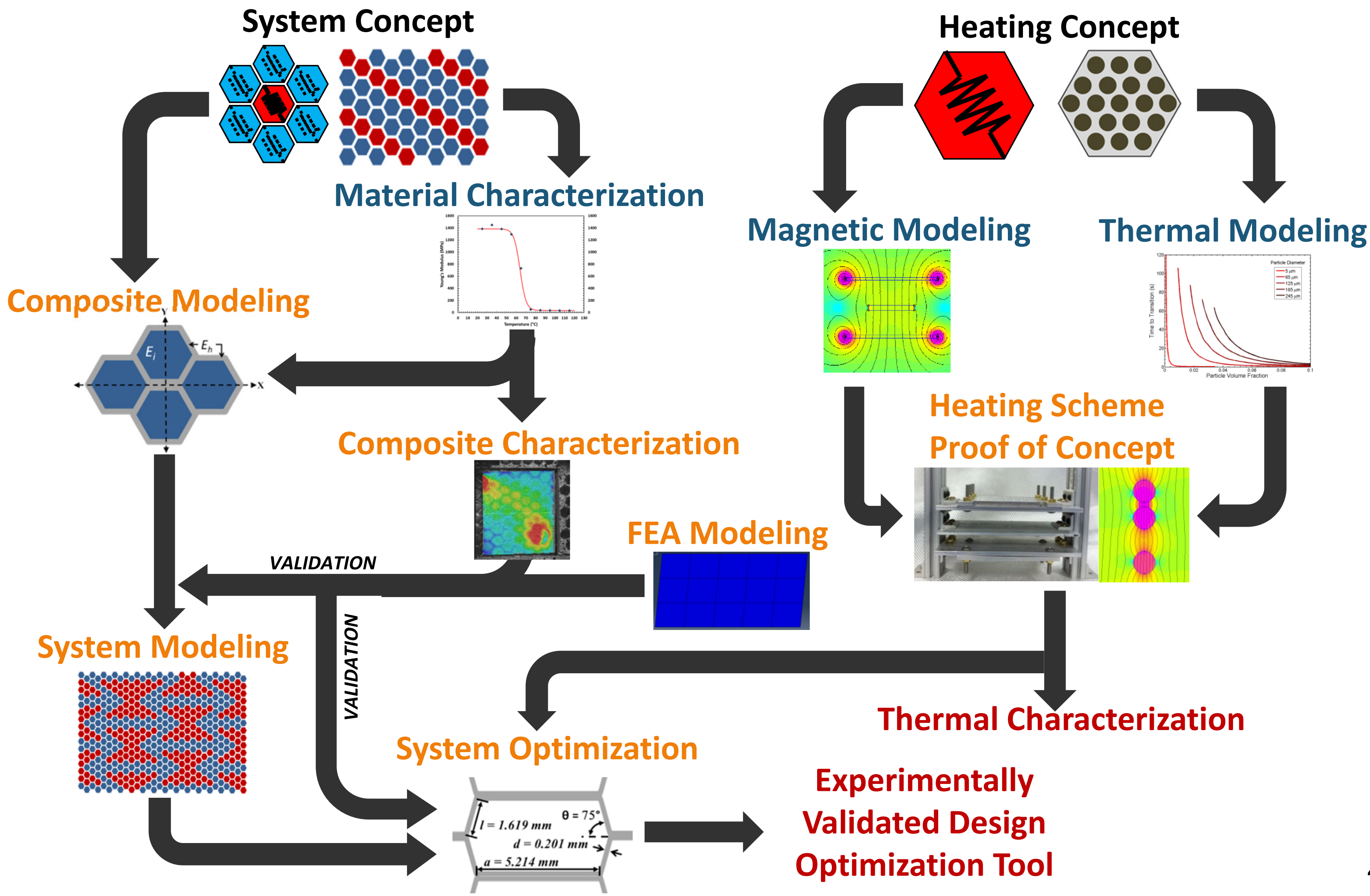


Heating Patterns

0 degrees
+45 degrees
-45 degrees
90 degrees
Diamond
Large Honeycomb
Auxetic
Isotropic
0 Poisson
Top/Bottom
Left/Right

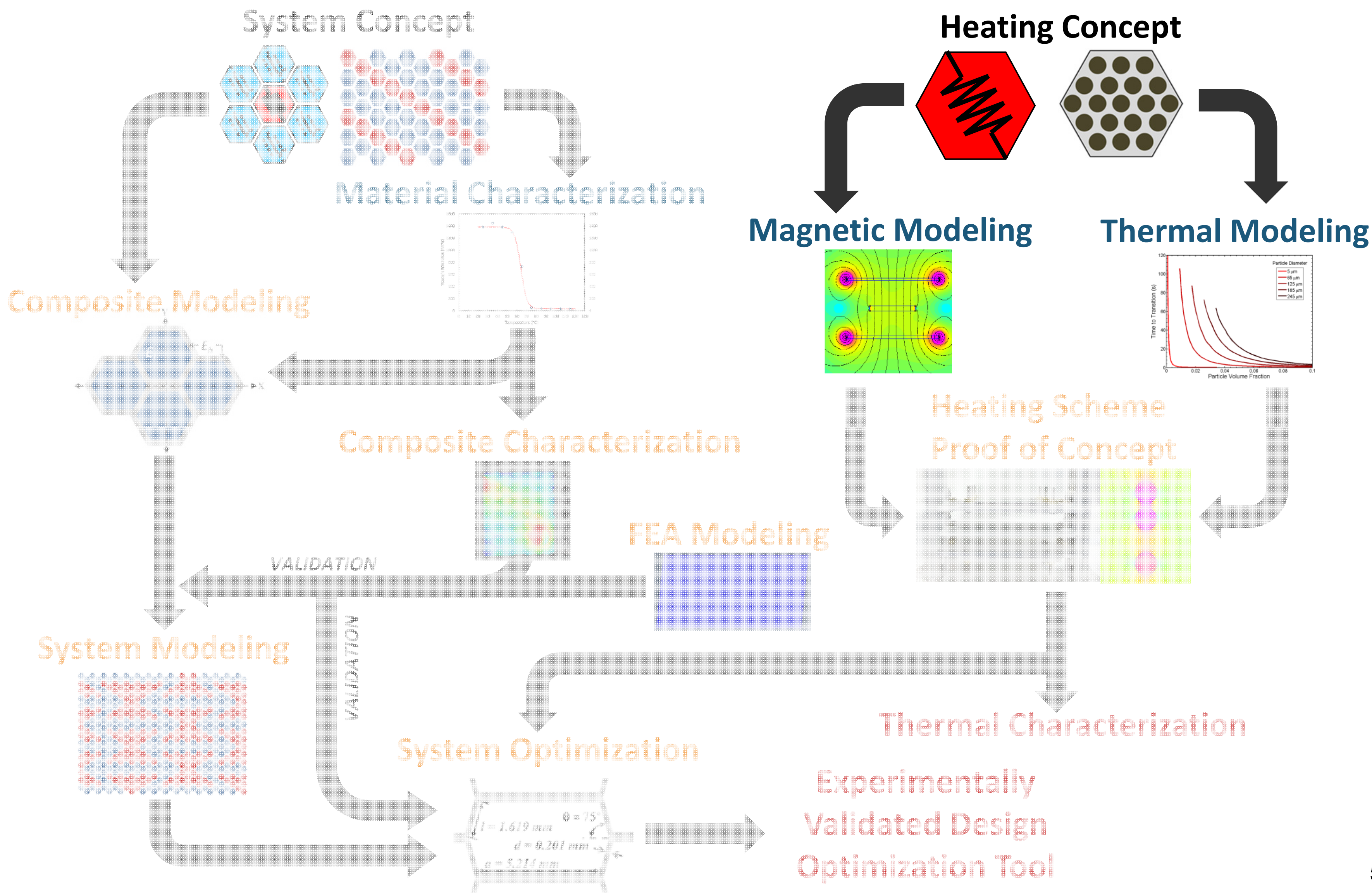
3

Project Roadmap



Approved for public release; distribution unlimited.

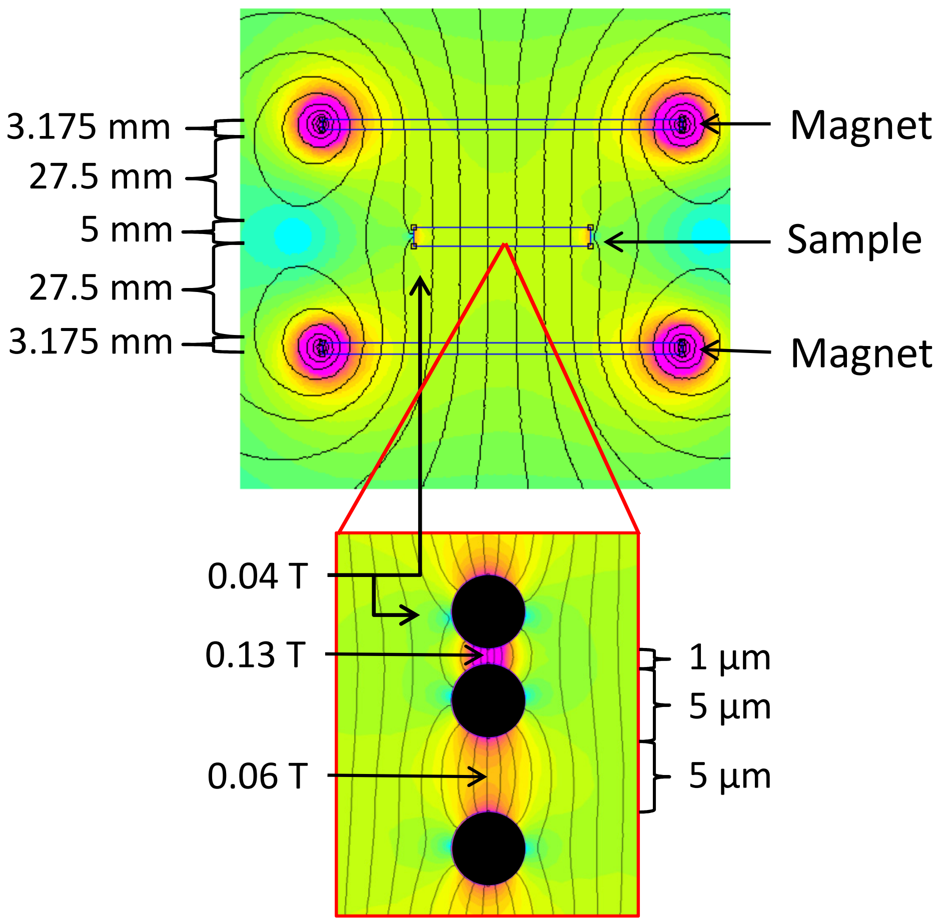
Project Roadmap



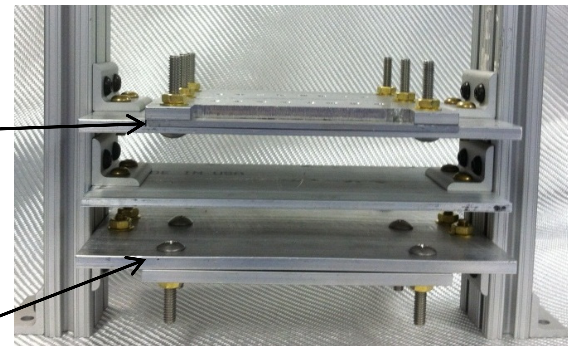
Approved for public release; distribution unlimited.

Magnetic and Thermal Modeling

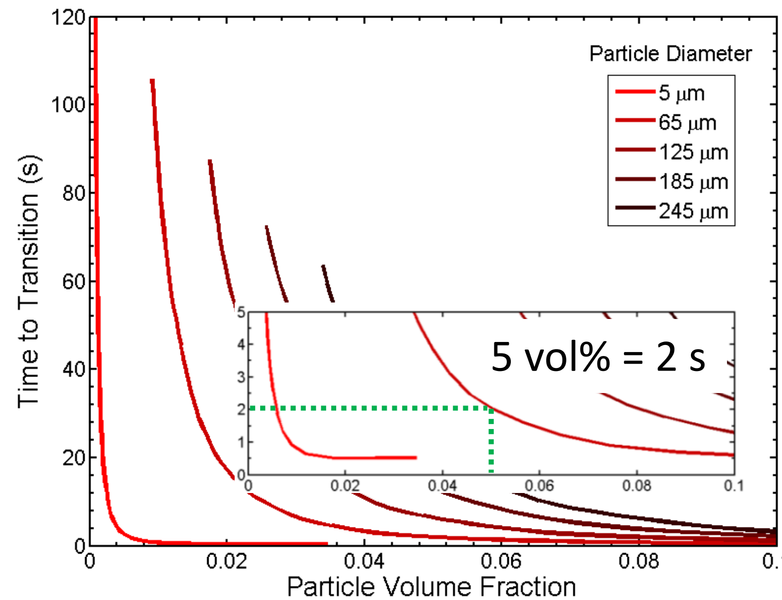
Magnetic Field Lines Between Two Magnets



Magnetic Field Lines b/t Ni Particles

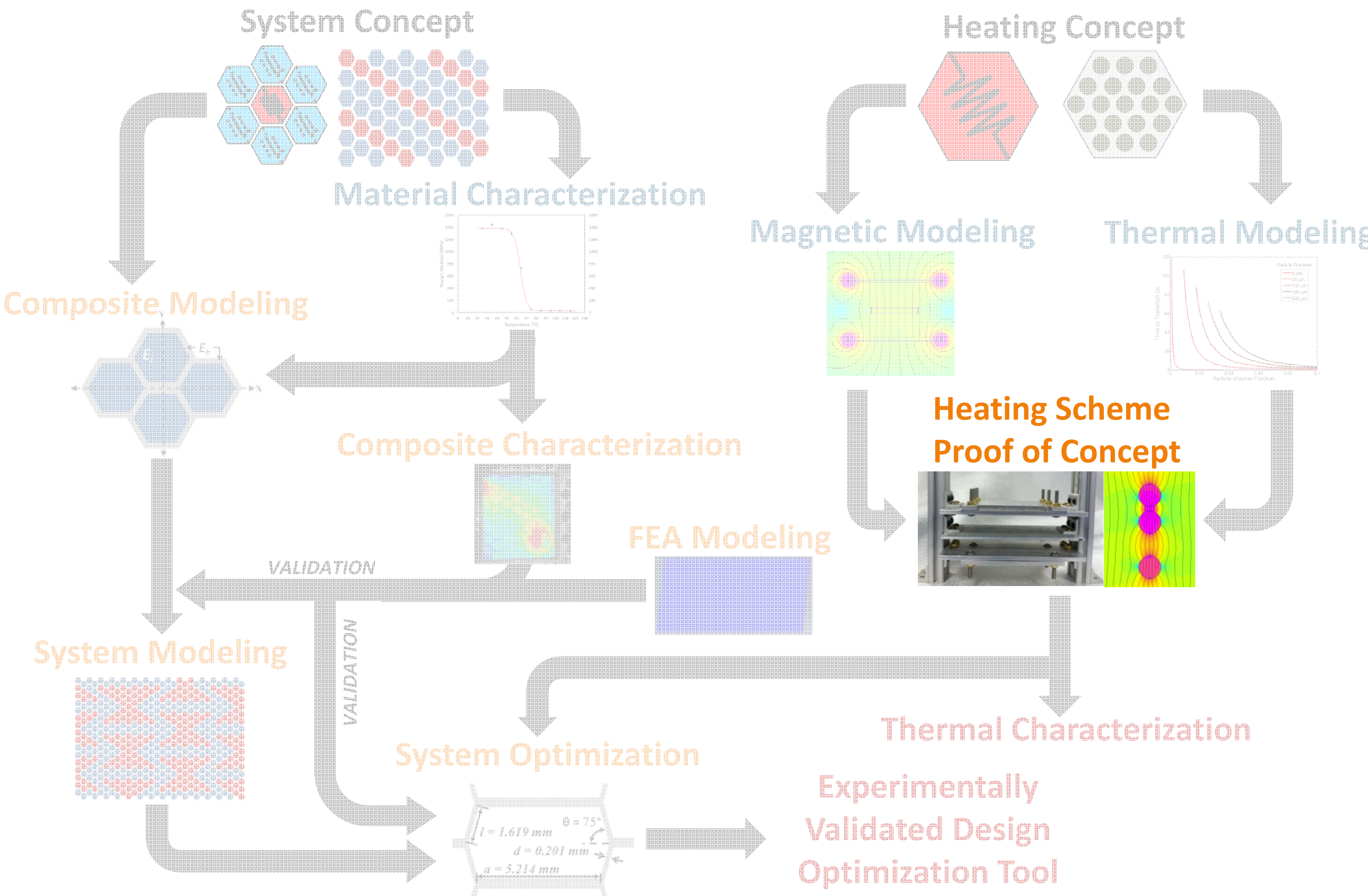


Nickel: 3-7 µm diameter
Epoxy SMP
Neodymium (NdFeB) N42SH magnets



6

Project Roadmap



7

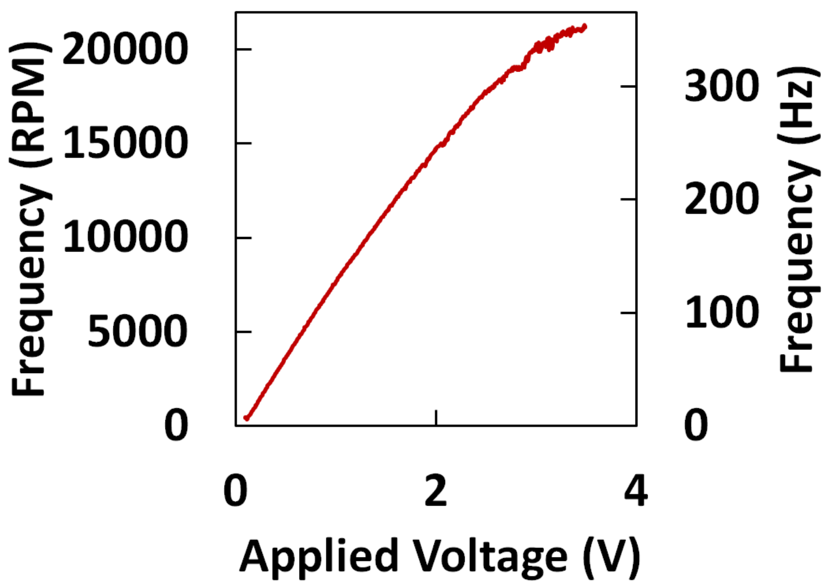
Approved for public release; distribution unlimited.

Heating Scheme Proof of Concept

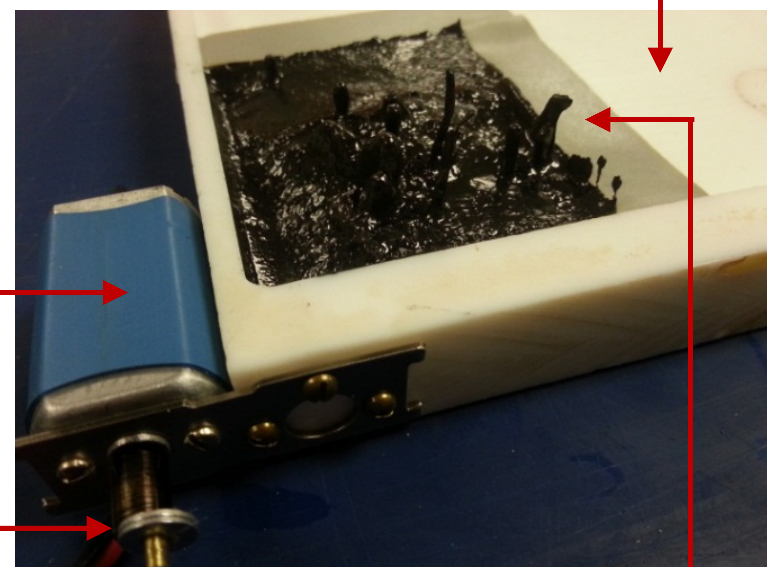
Velocity of a particle subject to a pulsating fluid

$$u = \frac{3\rho}{\rho + 2\rho_s} v_\infty$$

u particle velocity
ρ fluid density
ρ_s particle density
v_∞ imposed pulsating field



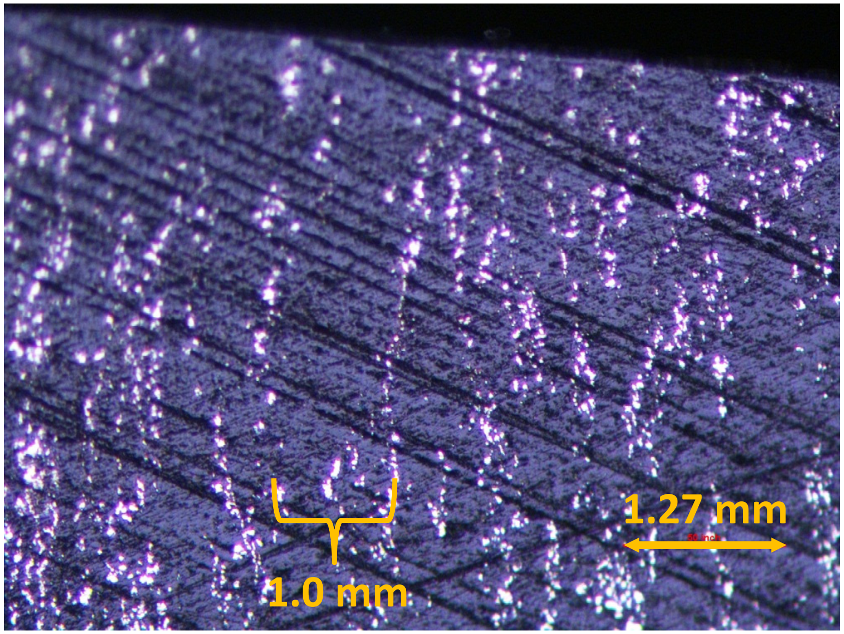
Offset Weight
Motor
Teflon® Mold

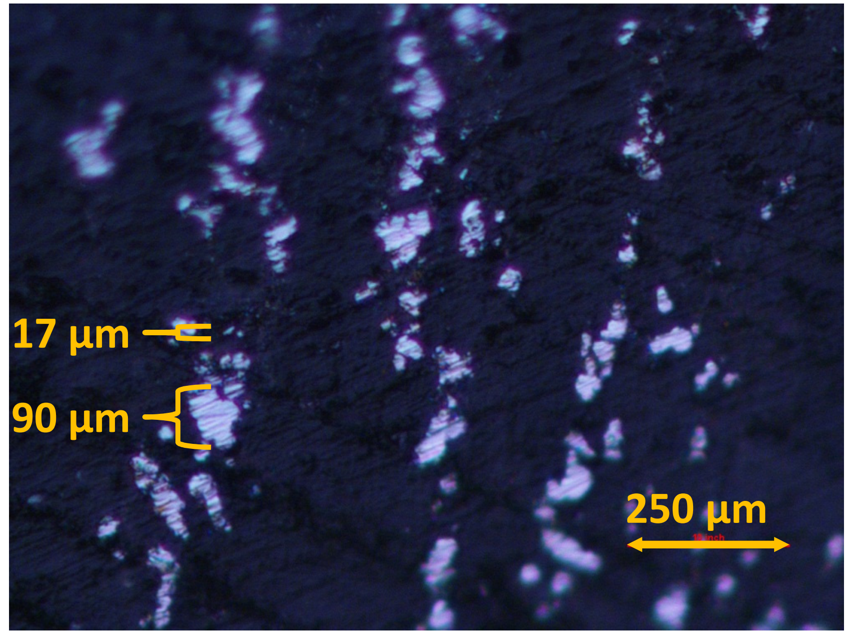


Peaks: magnetic field too strong
magnetic field unbalanced

D.V. Lyubimov, A.Y. Baydin, T.P. Lyubimova; *Particle Dynamics in a Fluid Under High Frequency Vibrations of Linear Polarization*, J. of Microgravity Science & Technology, vol. 25, pp 121-126, 2013

Heating Scheme Proof of Concept

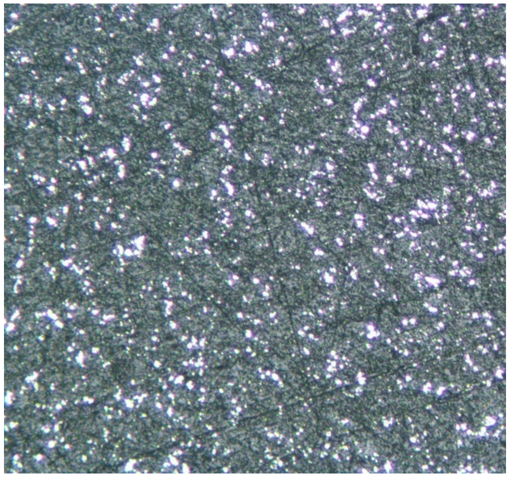




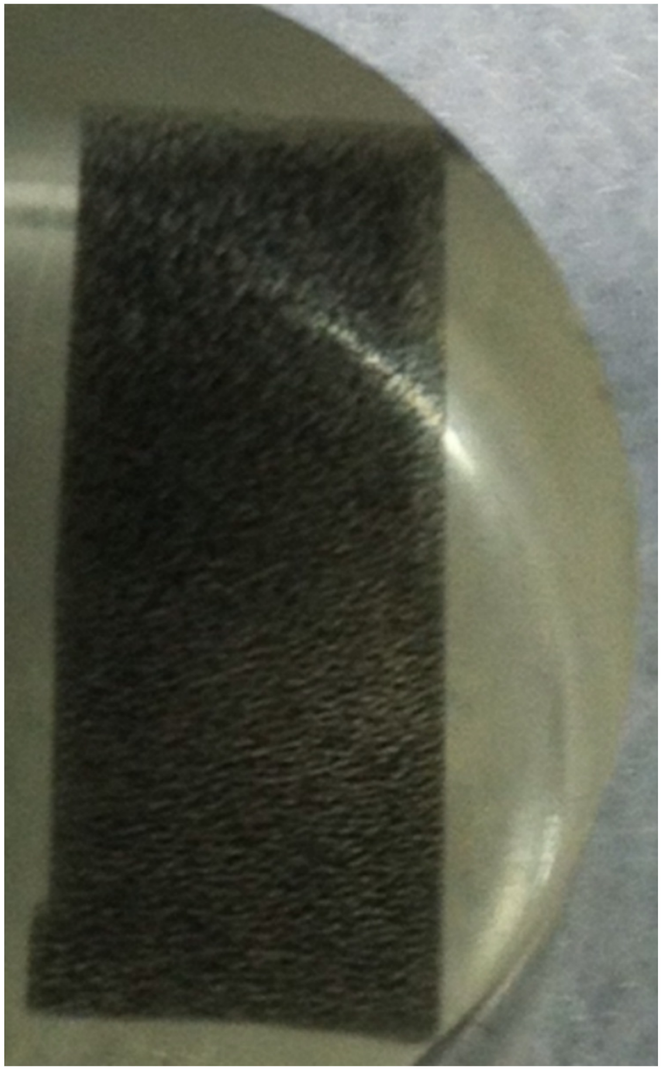
5 vol% 3-7 µm Nickel particles
Neodymium magnets 40mm separation
350 Hz vibration
212°F for 3 hours
Mold: 10 x 10 x 0.75 cm

ϕ_c =0.41 (50 µm diameter, δ_c 10 nm)
ϕ_{exp} =0.10
10 vol%, 10V, random orientation: 60s

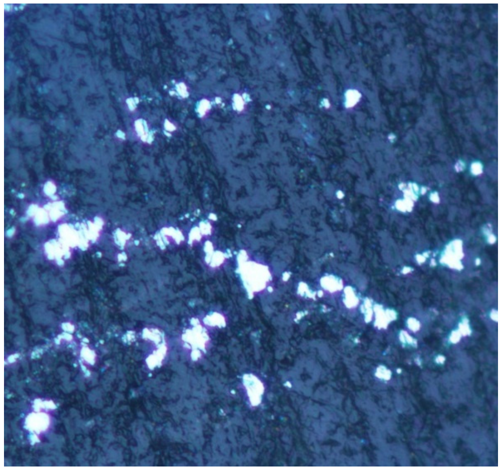
Heating Scheme Proof of Concept



End View of Nickel



End View of Particle Chains

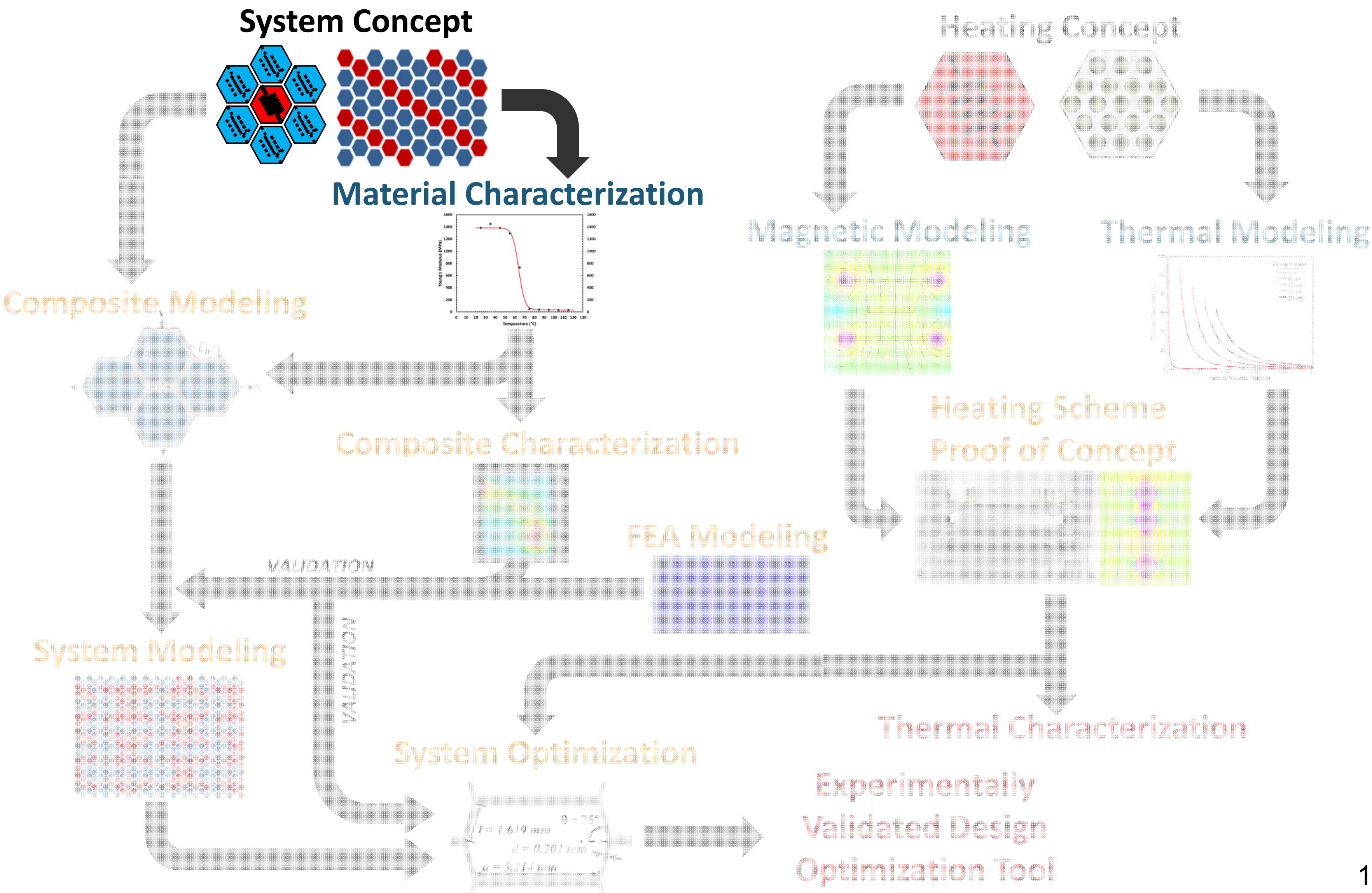


Side View Nickel

Tested several Copper, Steel, and NiChrome mesh electrodes
100x100 Cu most promising

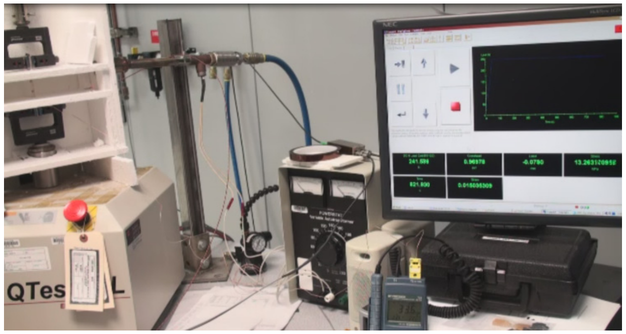
Current activation: 10V, ~60s

Project Roadmap



11

Epoxy SMP Characterization

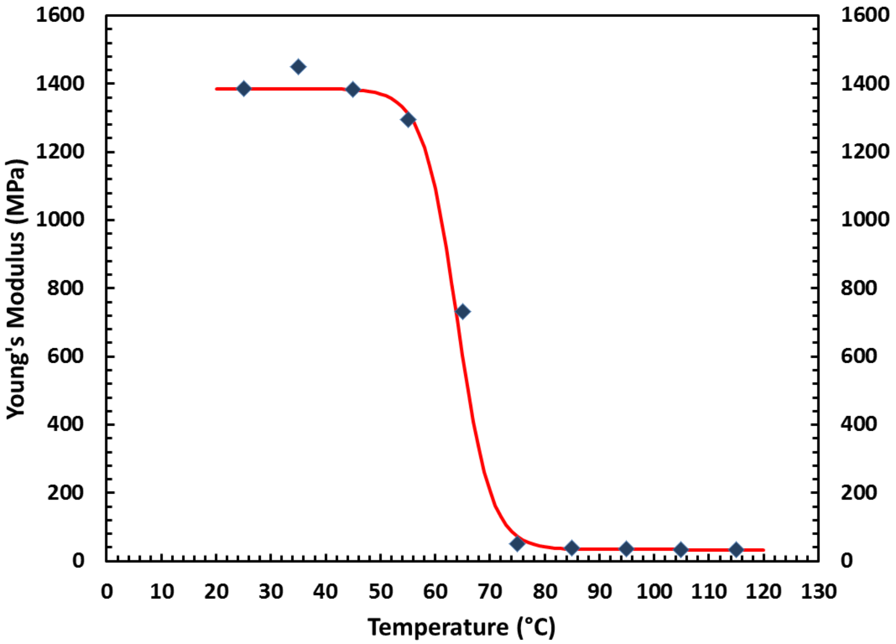


Epoxy SMP Characterization

Epoxy SMP Formulation

0.02 mol (7.28g) EPON 826
0.01 mol (2.3g) Jeffamine D230
100°C for 1.5hr, 130°C for 1hr

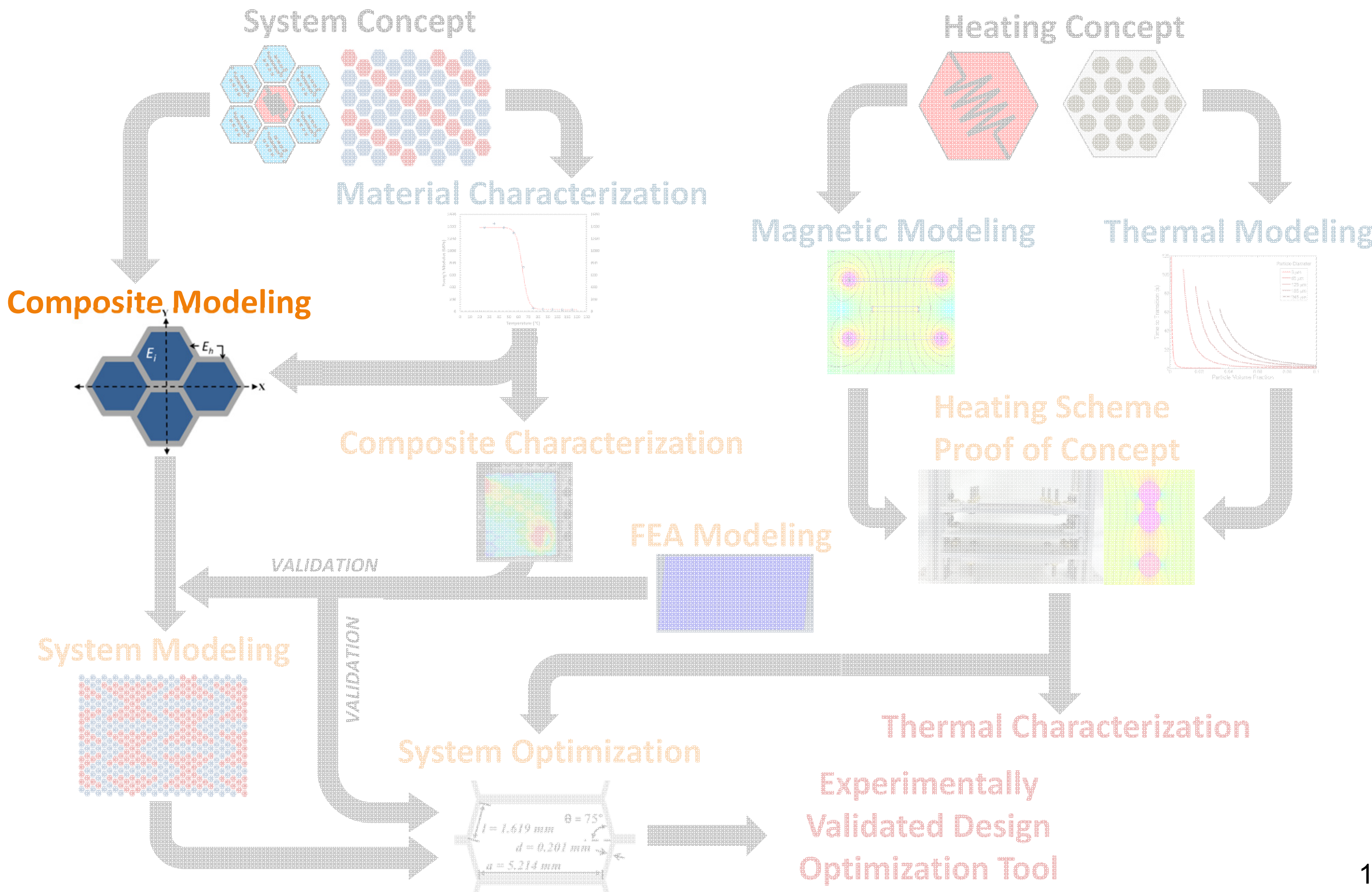
Experimental Results	
T_g	65 °C
E (ambient)	1300 MPa
E (115 °C)	19 MPa



Values consistent over several batches, 0-8 week sample age

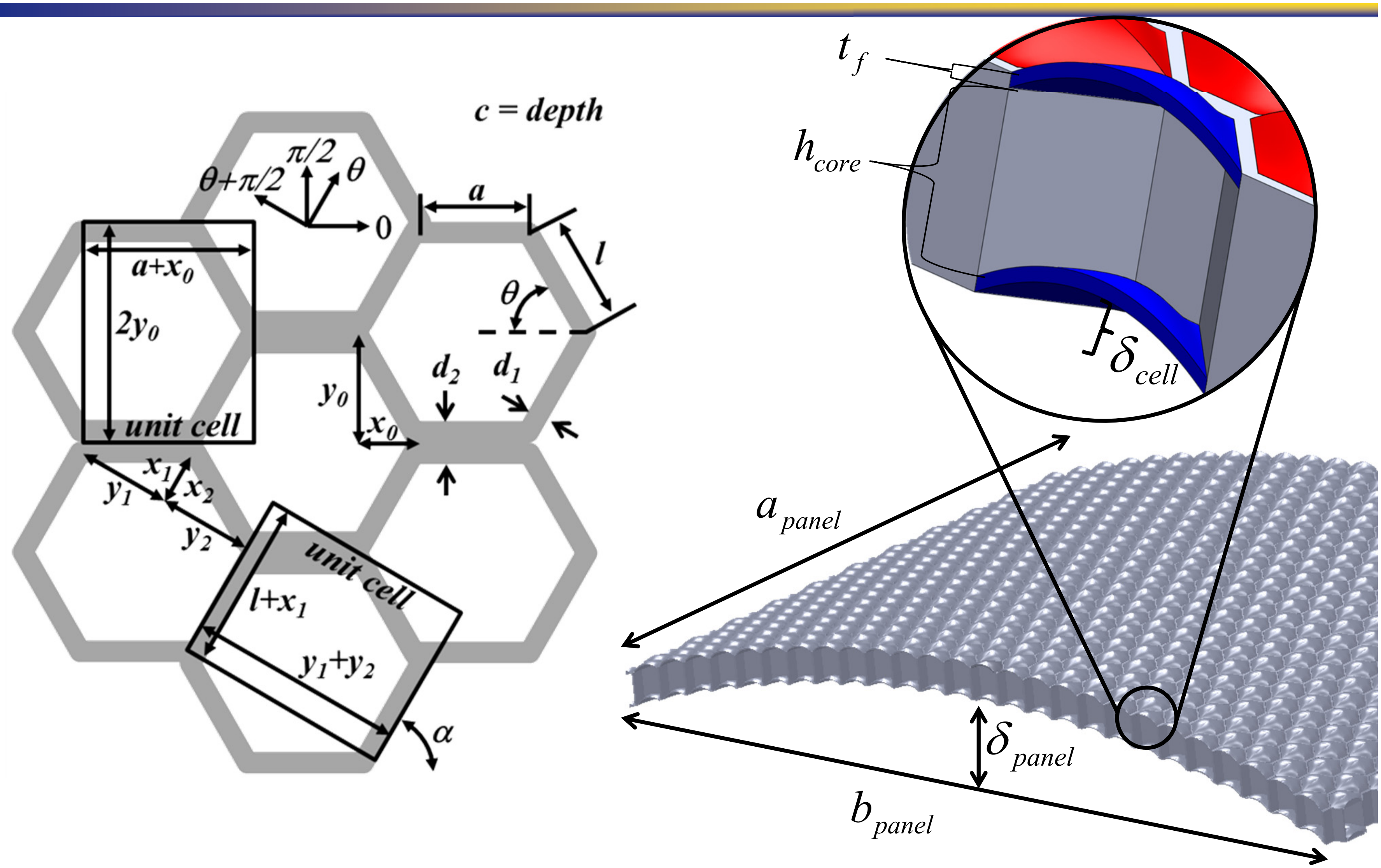
T Xie, IA Rousseau, *Facile tailoring of thermal transition temperatures of epoxy shape memory polymers,* Polymer, 2009

Project Roadmap

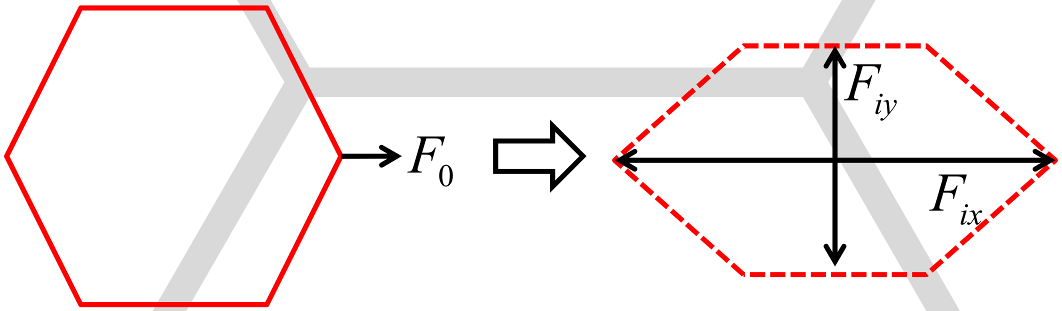


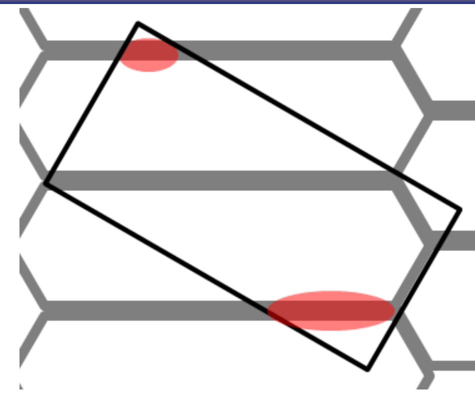
13

Composite Analytic Model

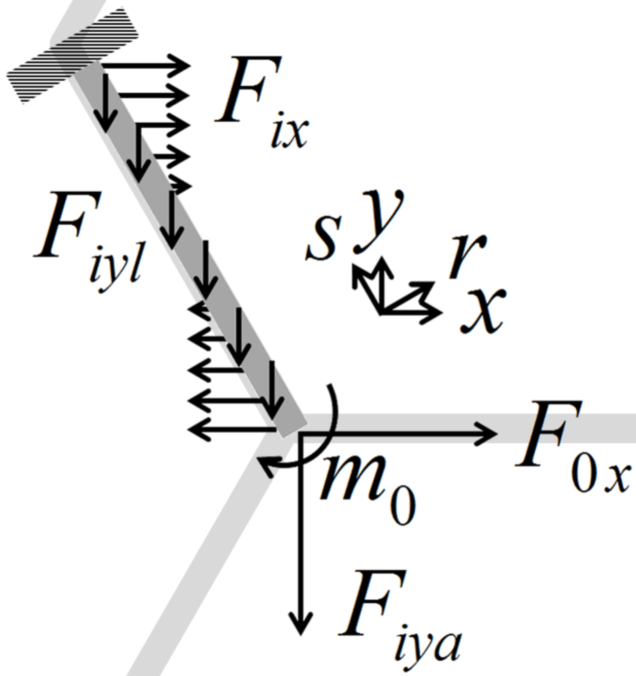


Composite Analytic Model





Non-compliant Geometry



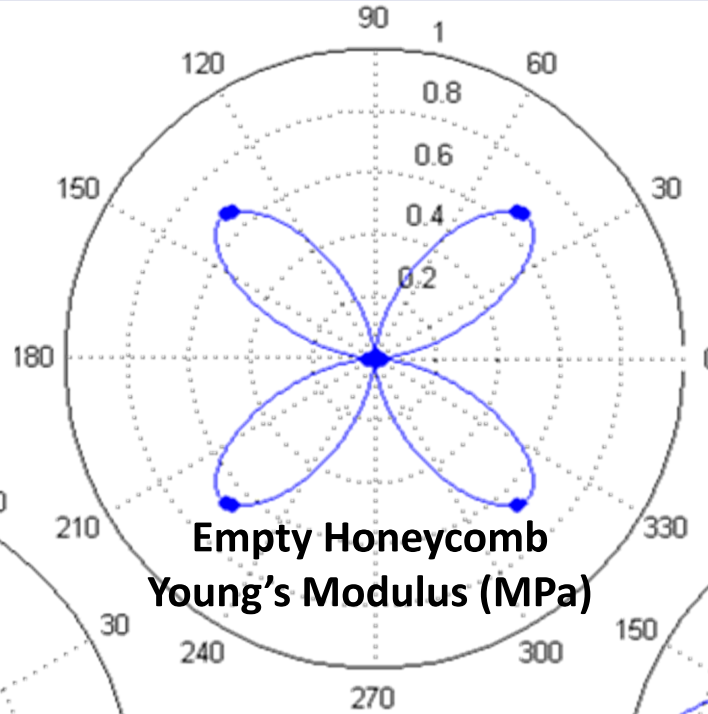
$$\delta_j = \sum_m \left\{ \left[\int_0^{L_m} \frac{N_m^2}{2E_m A_m} \partial z + \int_0^{L_m} \frac{M_{x,m}^2}{2E_m I_{x,m}} \partial z \right] \frac{\partial}{\partial F_j} \right\}$$

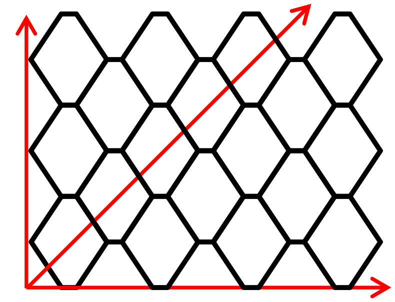
$$\delta_0 = \delta_a + 2\delta_{lr} + 2\delta_{ls}$$

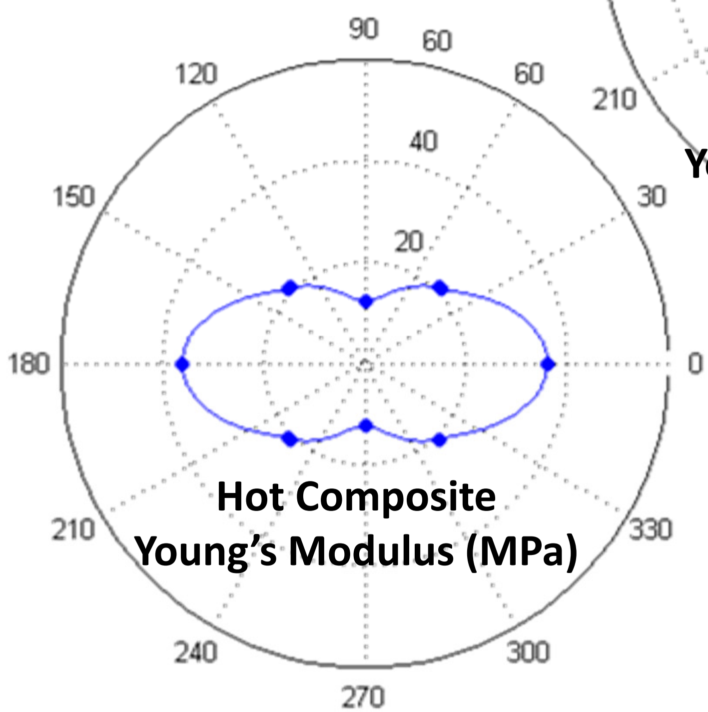
$$E_{c0} = \frac{F_{00}}{\delta_0} \frac{(a + x_0)}{2cy_0}$$

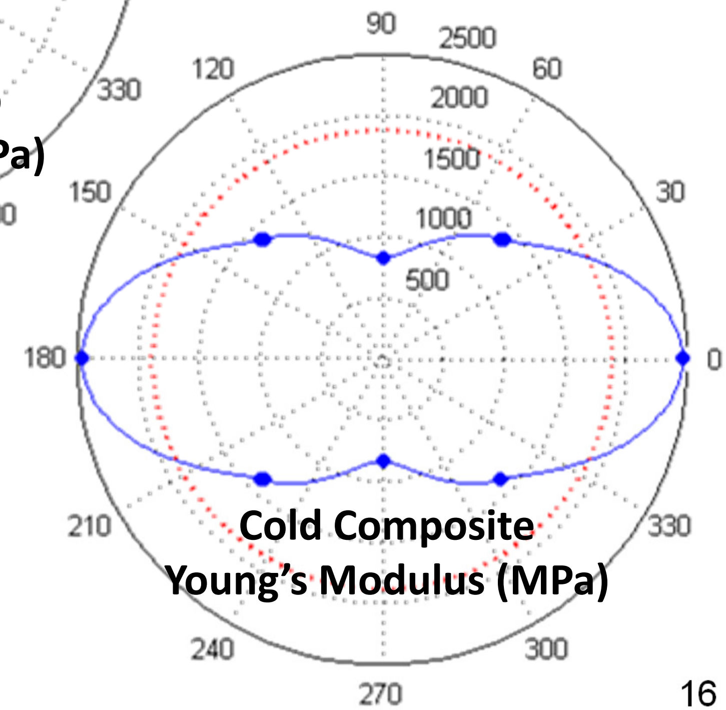
Composite Analytic Model

- Analytic Model

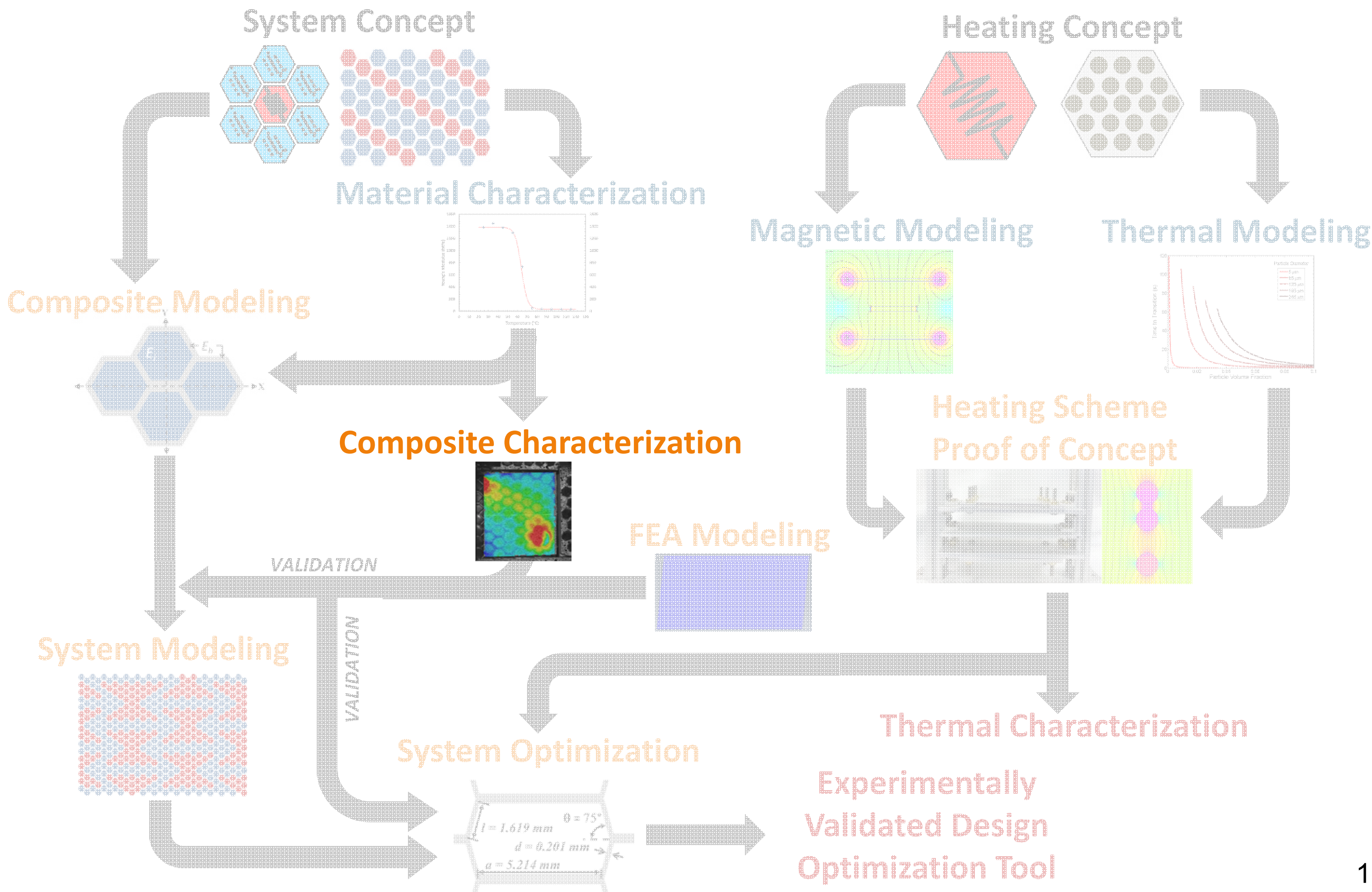






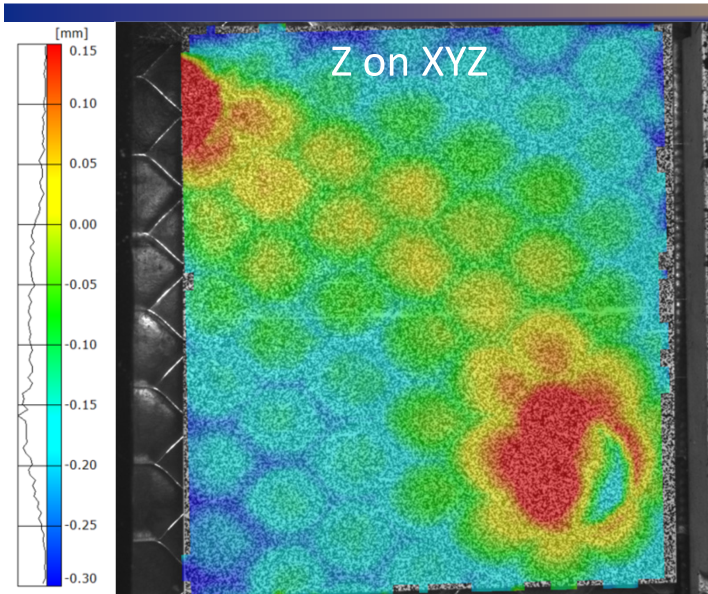


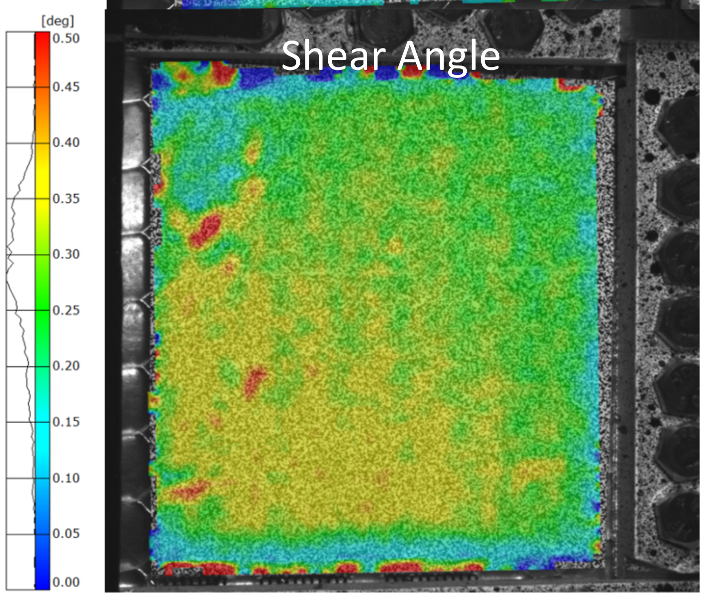
Project Roadmap

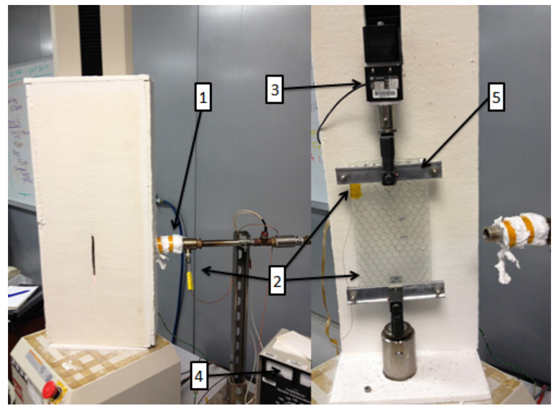


17

Composite Characterization



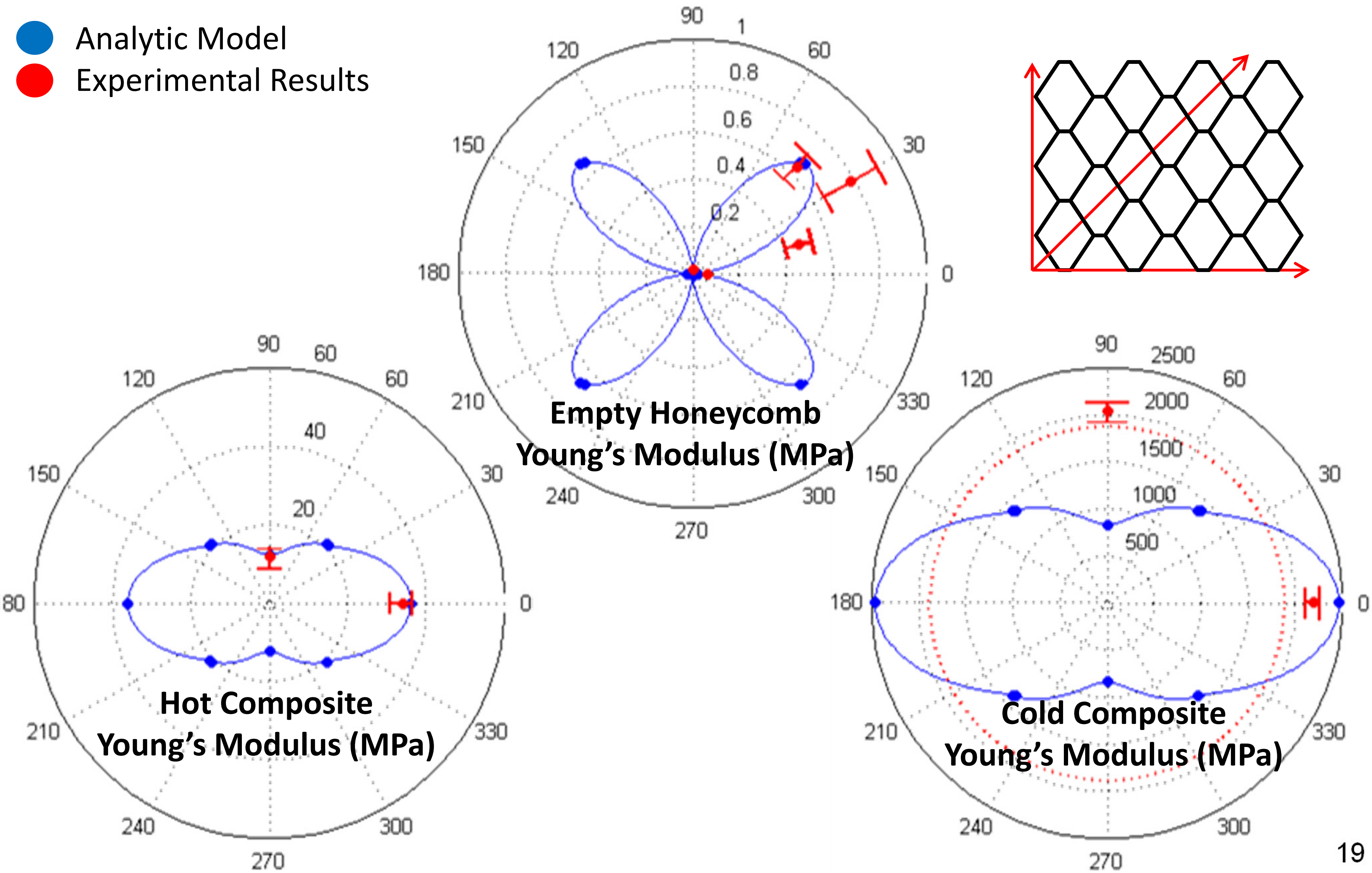




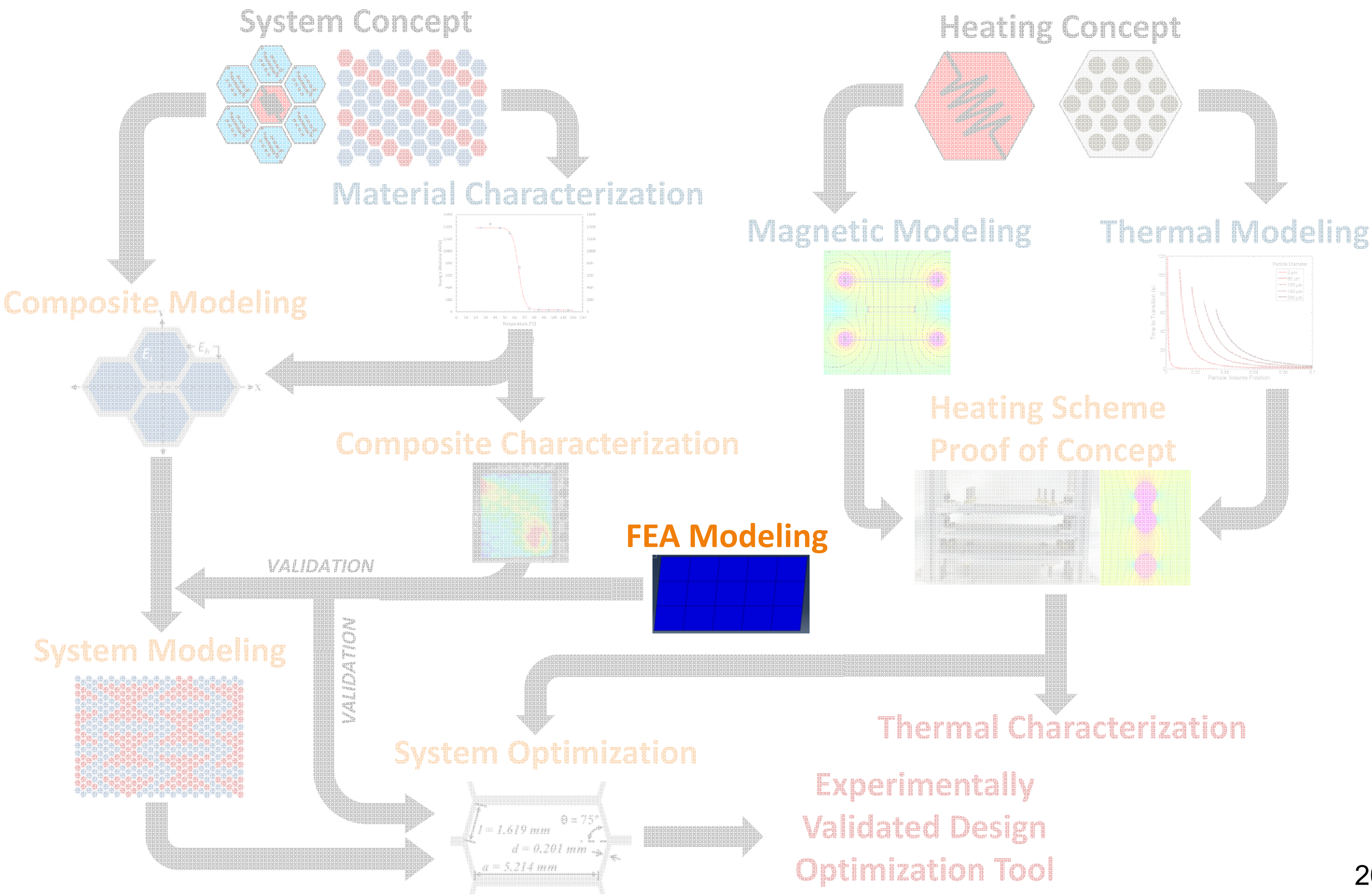
	23 °C	115 °C
E_{Epoxy}	1.3 GPa	19 MPa
E_{HX}	62.8 kPa	
E_{HY}	16.6 kPa	
E_{CX}	2.19 GPa	33.9 MPa
E_{CY}	2.04 GPa	11.8 MPa

	23 °C	115 °C
G_{Epoxy}	1.27 GPa	1.06 MPa
G_{CXY}	1.19 GPa	13.9 MPa
G_{CYX}	1.13 GPa	13.0 MPa

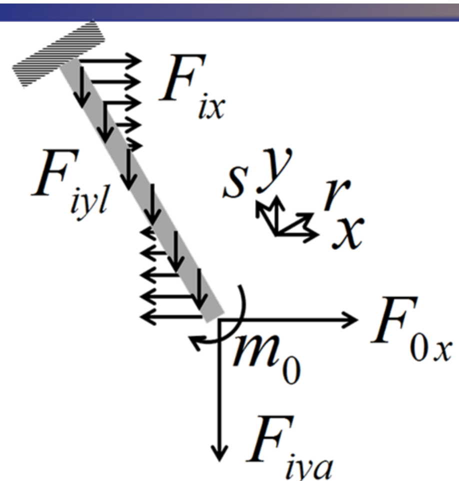
Composite Characterization



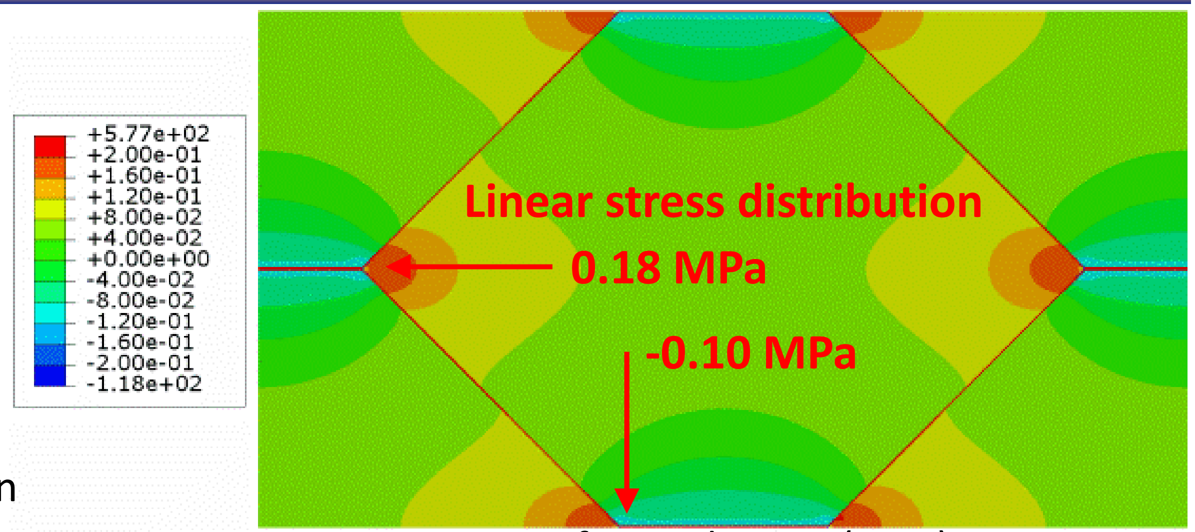
Project Roadmap



Composite FEA Model

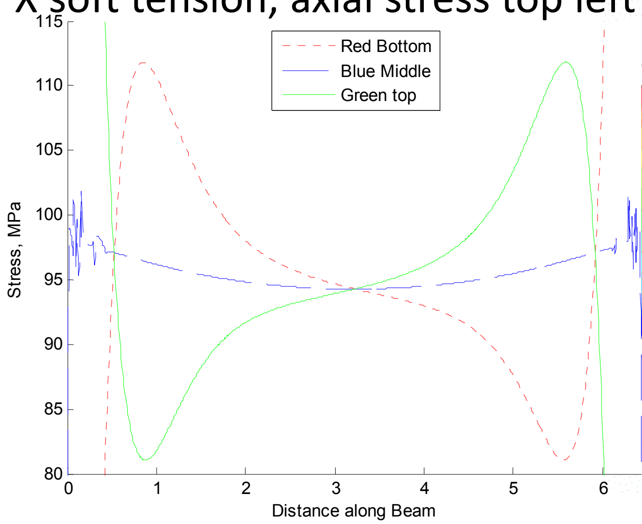


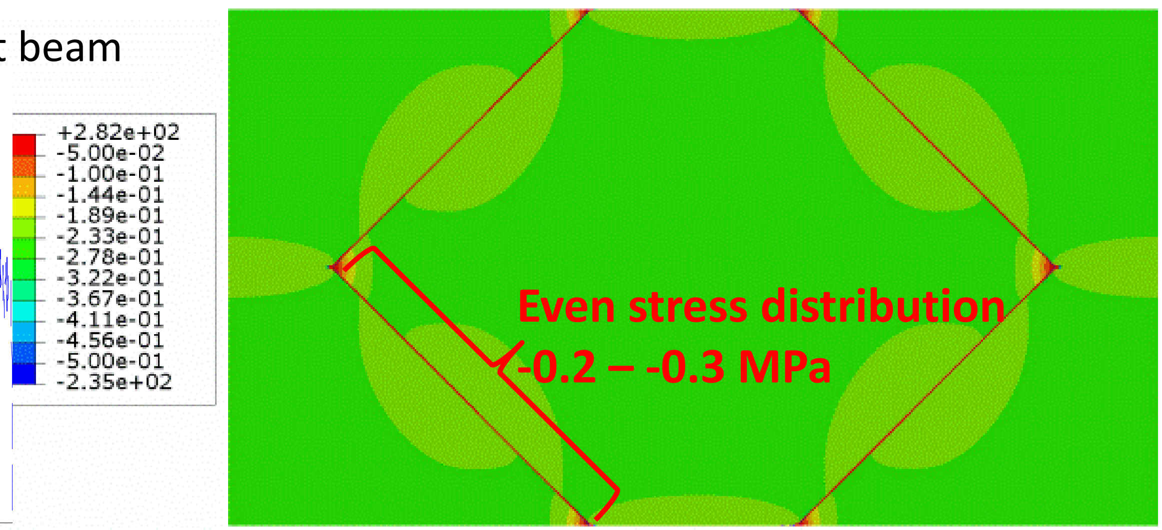
FEA supports force distribution assumption of analytic model



X Soft Tensile, S11 (MPa)

X soft tension, axial stress top left beam

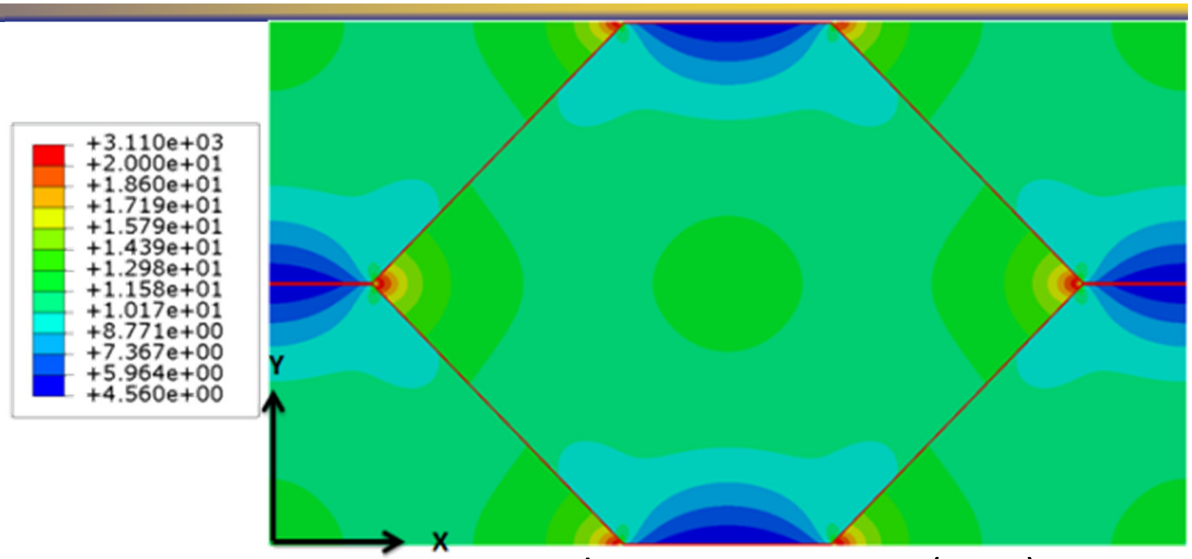




X Soft Tensile, S22 (MPa)

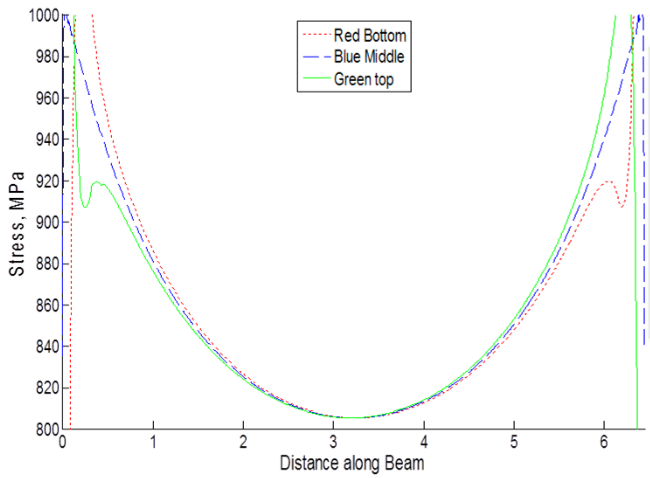
Composite FEA Model

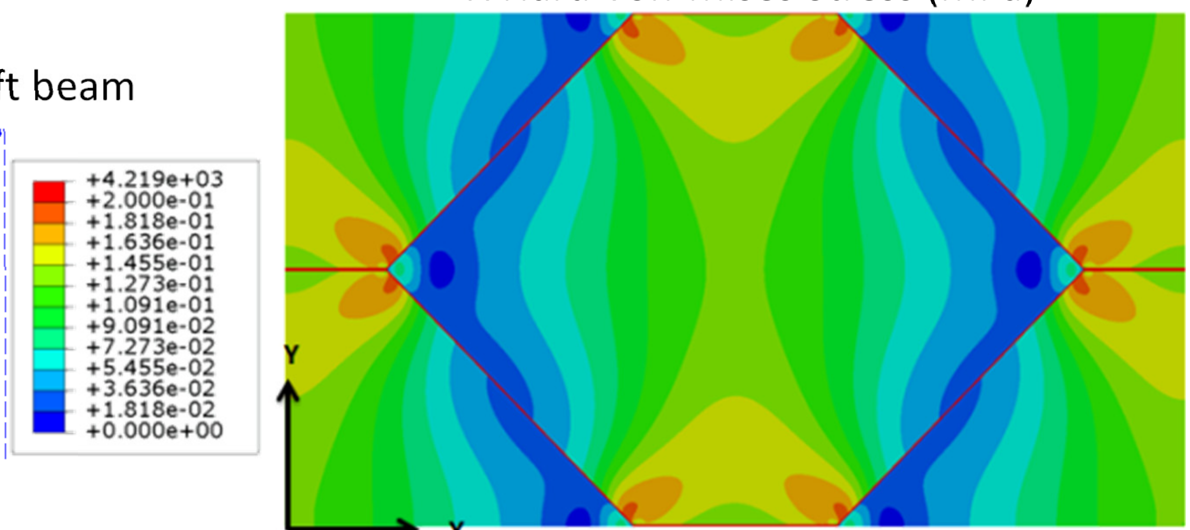
	23 °C	115 °C
E_{CX}	1.40 GPa	52.4 MPa
E_{CY}	1.08 GPa	17.9 MPa
G_{CXY}	0.81 GPa	16.3 MPa
G_{CYX}	0.81 GPa	16.4 MPa



X Hard Von-Mises Stress (MPa)

X hard tension, axial stress top left beam

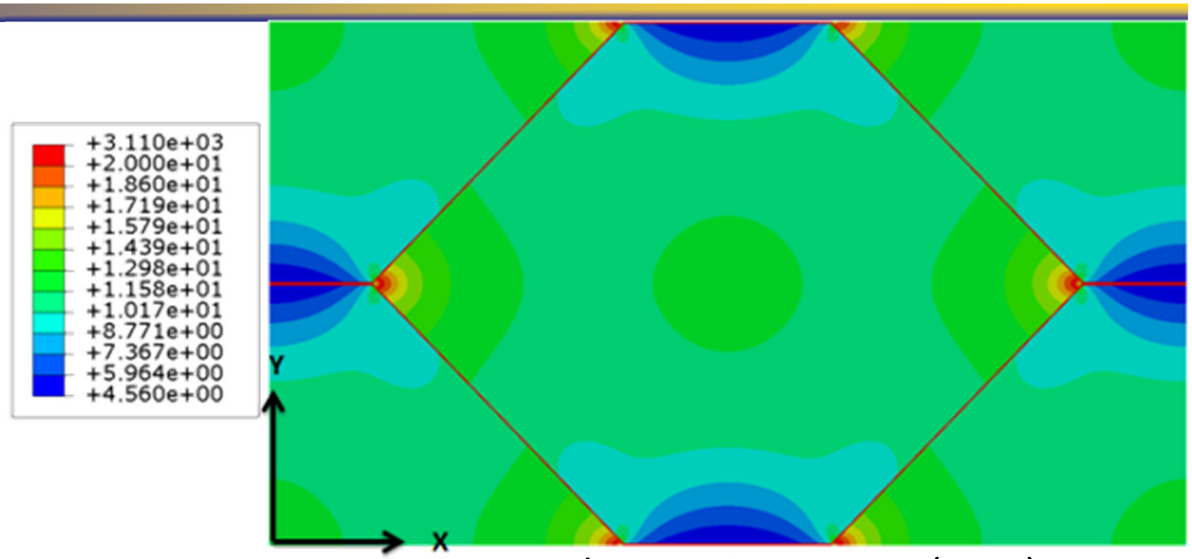




XY Hard Von-Mises Stress (MPa) 22

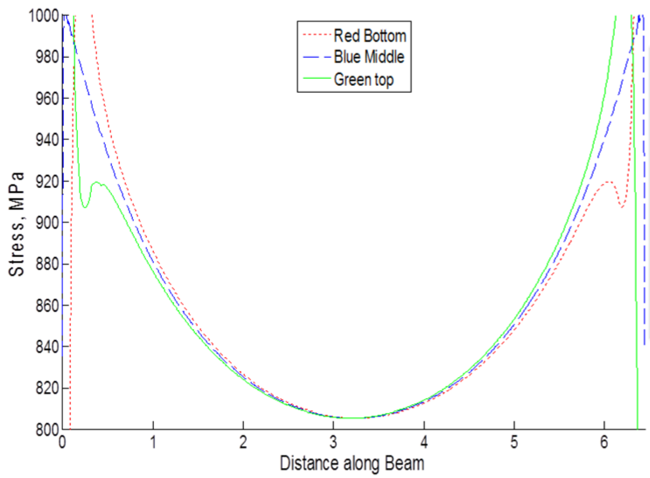
Composite FEA Model

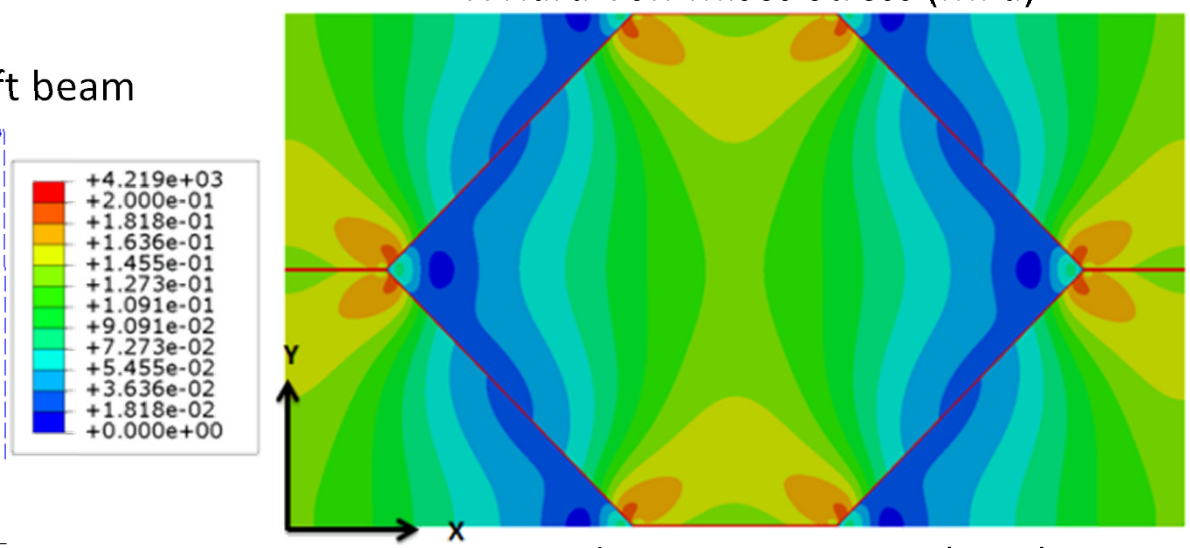
	23 °C	115 °C
E_{CX}	TBD	TBD
E_{CY}	TBD	TBD
G_{CXY}	TBD	TBD
G_{CYX}	TBD	TBD



X Hard Von-Mises Stress (MPa)

X hard tension, axial stress top left beam





XY Hard Von-Mises Stress (MPa)

23

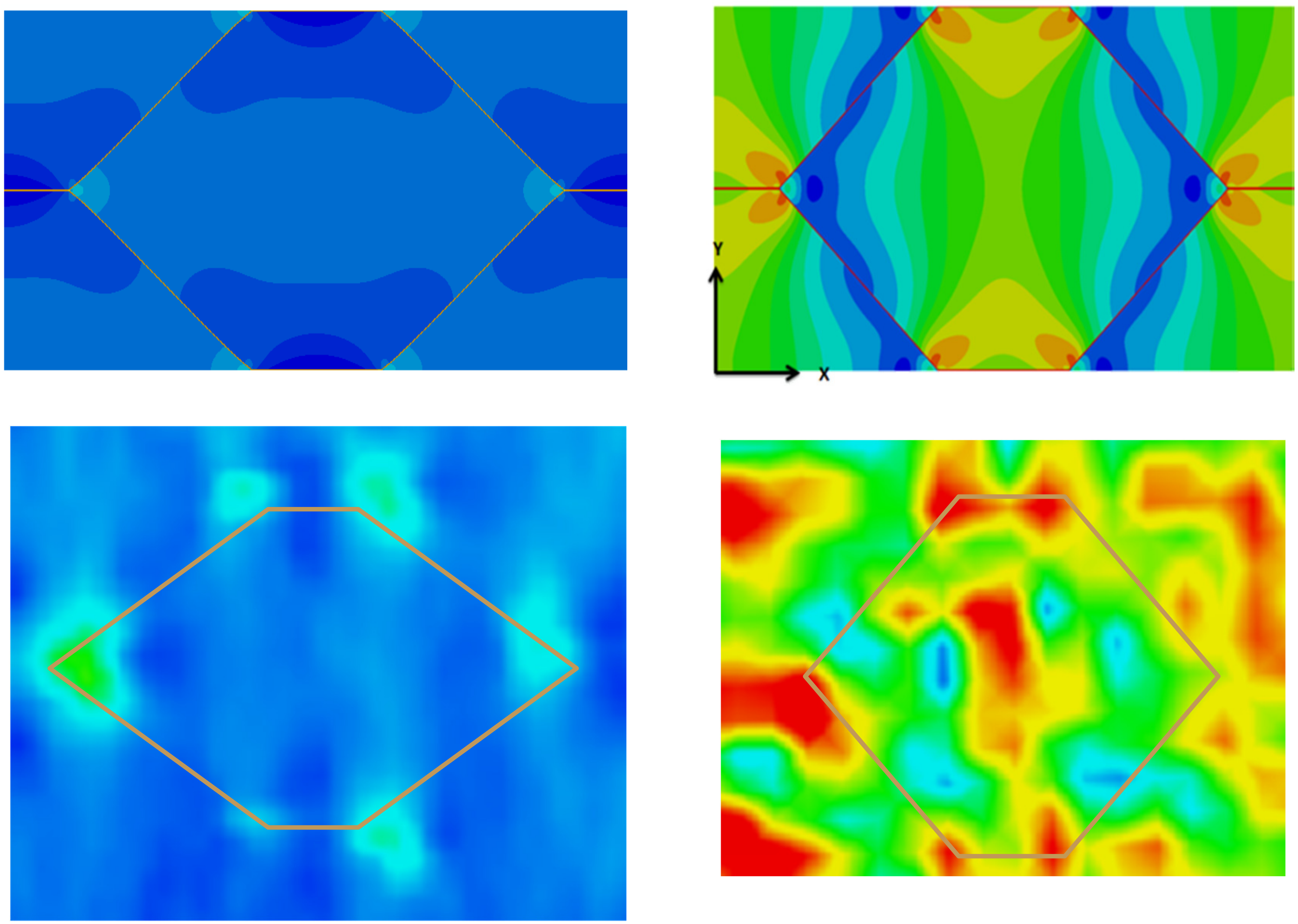
Composite FEA Model

Tension (Von-Mises Stress)

Shear (Von-Mises Stress)

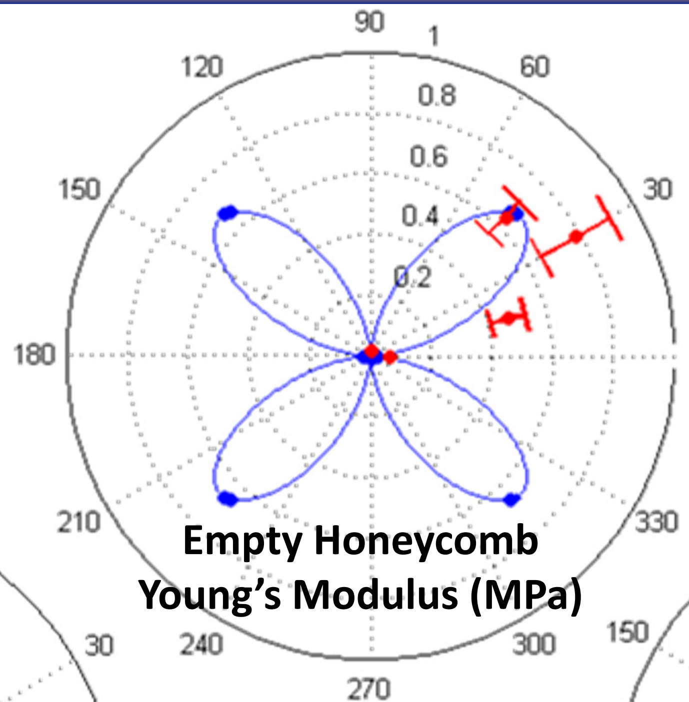
FEA

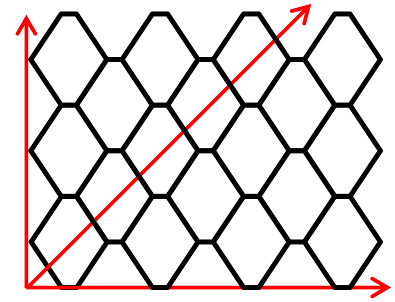
DIC

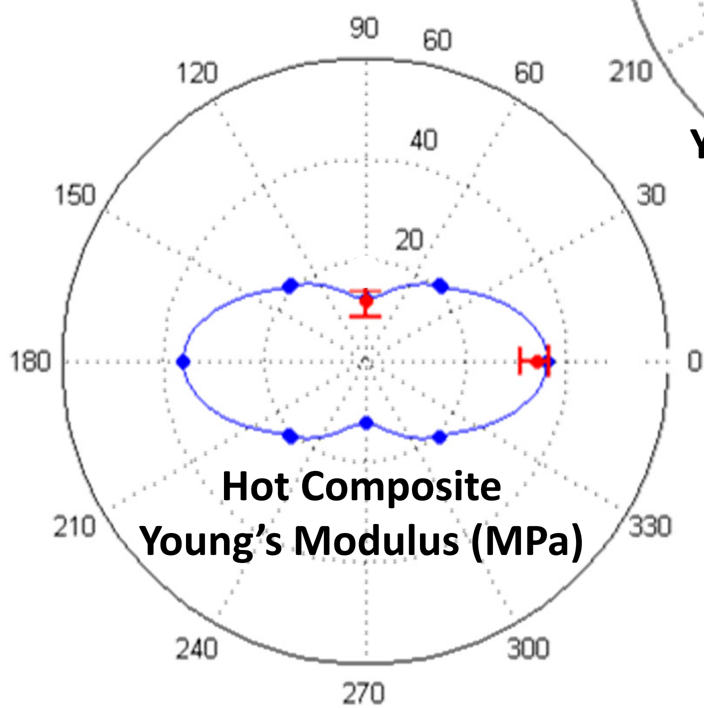


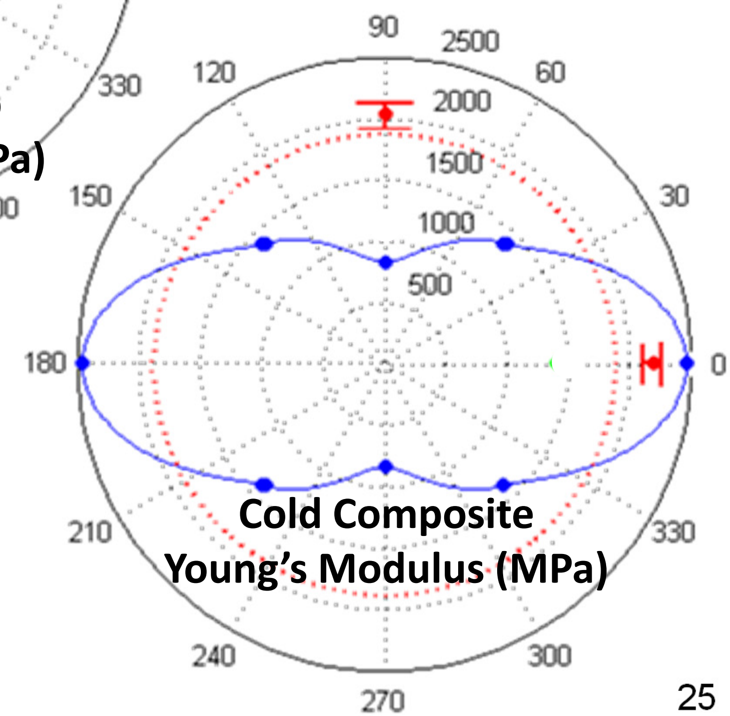
Composite FEA Model

- Analytic Model
- Experimental Results
- FEA Results





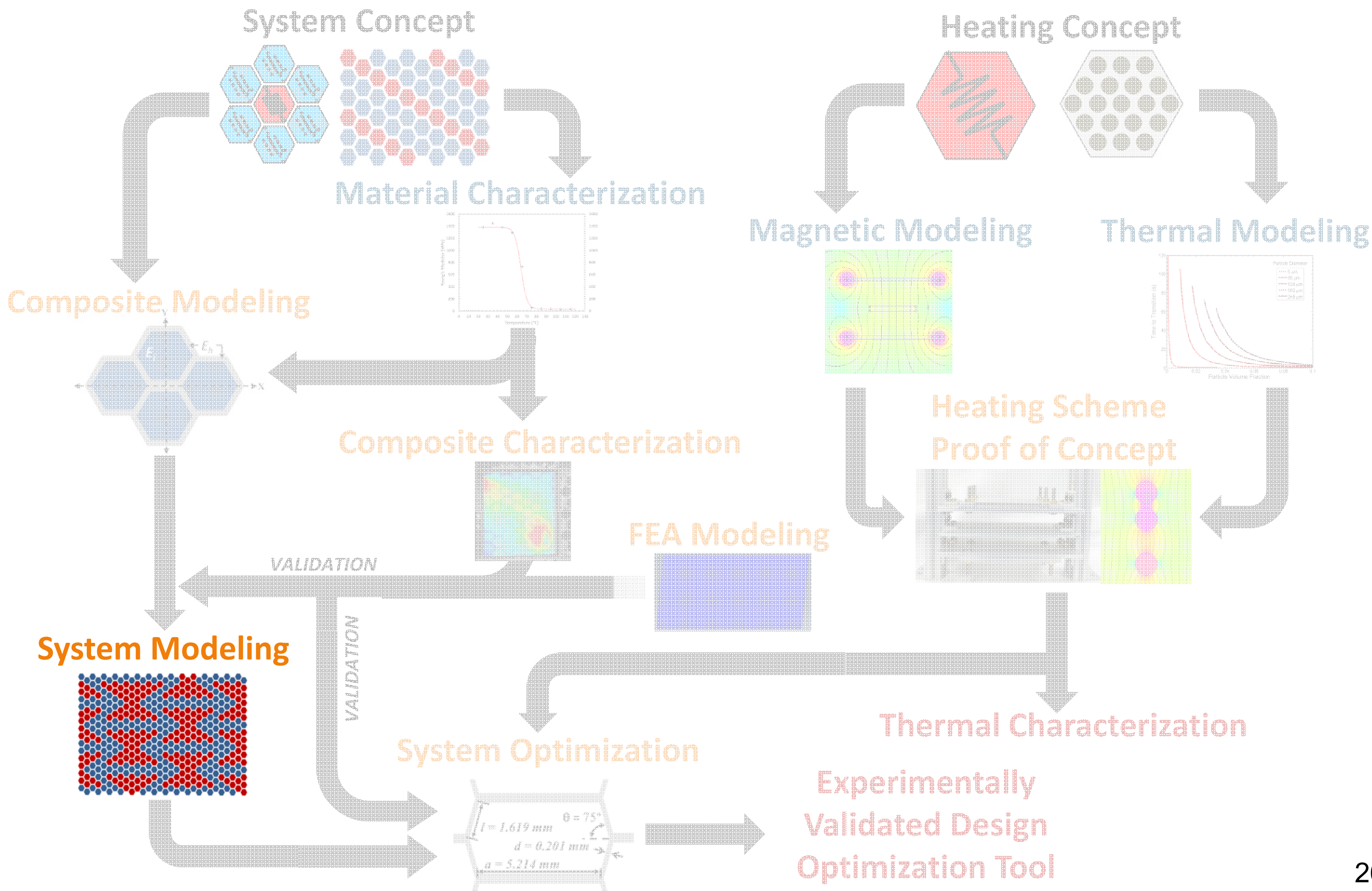




25

Approved for public release; distribution unlimited.

Project Roadmap



26

System Modeling

Low fidelity FEA
Homogenization scheme using
effective composite properties
Plane Stress (z direction neglected)
In-plane only
Calculates effective E_x, E_y, G_{xy}, G_{yx}
given heating pattern

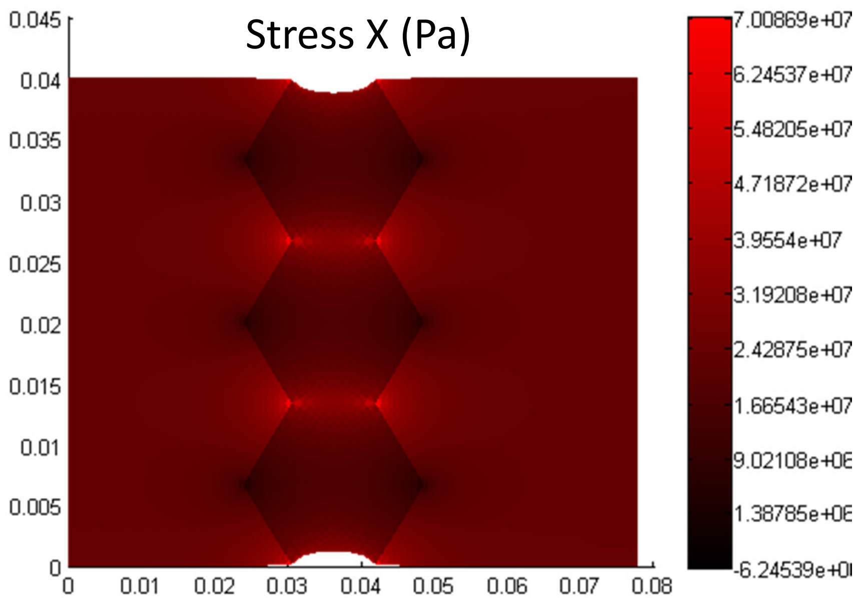
Material Stiffness Matrix

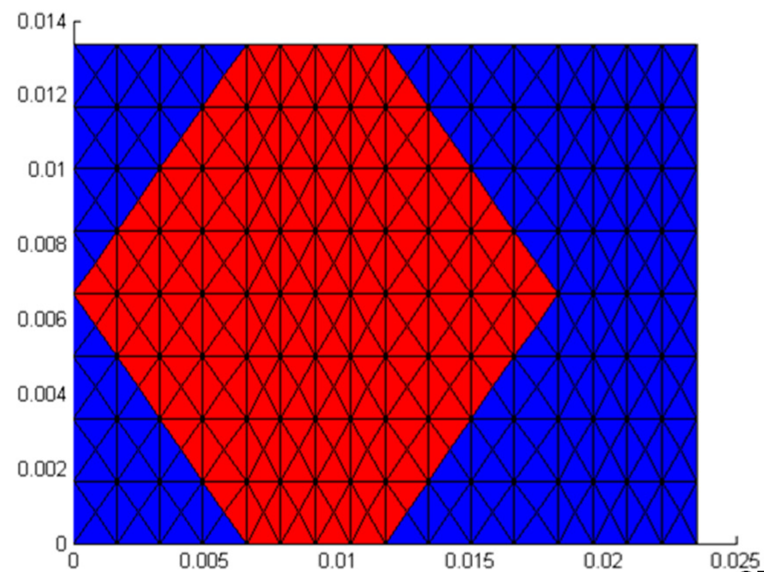
$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \\ \varepsilon_{21} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & 0 & 0 \\ 0 & 0 & \frac{1}{G_{12}} & \frac{\mu_{12,21}}{G_{21}} \\ 0 & 0 & \frac{\mu_{21,12}}{G_{12}} & \frac{1}{G_{21}} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \\ \sigma_{21} \end{bmatrix}$$

$$\mu_{12,21} = \frac{1}{\mu_{21,12}} = \frac{\left(l^3 + a^3\cos^2(\theta)\right)\left(a + x_0\right)}{2y_0 a^3 \cos(\theta)\sin(\theta)}$$

Non-zero shear coupling (Chentsov) coefficients

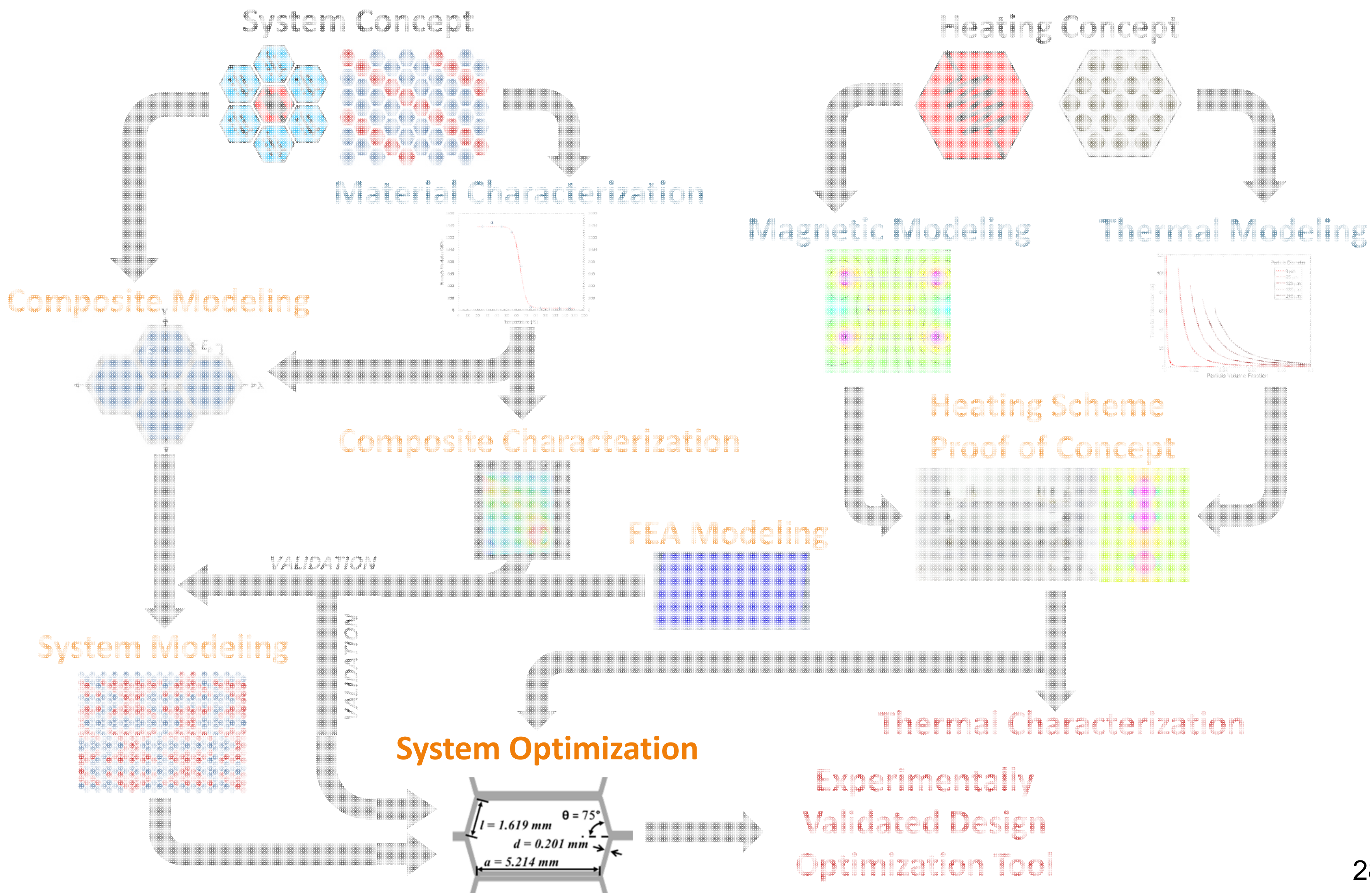
10% Strain X Direction
Stress X (Pa)





27

Project Roadmap



28

Honeycomb Geometry Optimization

Design Variables

$$0 \le l\,(m) < \infty$$
$$0.00005 \le d\,(m) < \infty$$
$$0 \le a\,(m) < \infty$$
$$0 \le \theta \le \pi/2$$
$$0 \le h_{core}\,(m) < \infty$$
$$0 \le t_f\,(m) < \infty$$

Ex. Optimization Function

$$F_{ext} = ave(E_{call})\varepsilon_{max} b_{panel}(h_{core} + 2t_f)$$

MAS Program Constraints

$$\delta = \delta_{panel} + \delta_{cell} \le 2.54\ mm$$
$$\delta_{panel} = \frac{C_0 w b_{panel}^4}{6E_f h_{core}^2 t_f}\left(\frac{1-\nu_f^2}{0.91}\right)$$
$$\delta_{cell} = \frac{C_0 w \min(2y_0, a+x_0)^4}{E_i t_f^2}\left(\frac{1-\nu_i^2}{0.91}\right)$$
$$W_{skin\,max} \le 4.6\frac{kg}{m^3} = \rho_{skin}(h_{core} + 2t_f)$$
$$\rho_{skin} = \rho_{core}\frac{h_{core}}{h_{core}+2t_f} + \rho_f\frac{2t_f}{h_{core}+2t_f}$$

Self-Imposed Constraints

$$\varepsilon_{x\max} > 0.1$$
$$\varepsilon_{y\max} > 0.1$$
$$\frac{1}{2} < \frac{2y_0}{a+x_0} < 2$$

Equation Constraints

Unit Cell Equations

$$\frac{a}{l}\begin{cases} \le \dfrac{\sin(\theta)}{\sin(\theta)\cos(\theta)} \\ \le \dfrac{2\sin(\theta) - \sin(2\theta)\cos(\theta)}{\sin(\theta)\cos(\theta)} \\ \ge 0 \\ \ge \dfrac{\sin\left(\dfrac{3\pi}{2}+2\theta\right)}{\cos(\theta)} \end{cases}$$

Thin Beam Theory

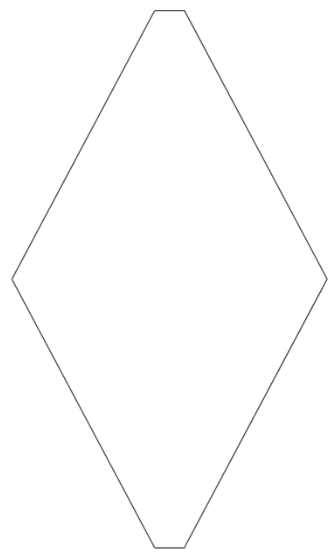
$$d\begin{cases} \le \dfrac{a}{8} \\ \le \dfrac{l}{8} \end{cases}$$

Sandwich Plate Deflection

$$\delta \le (h_{core} + 2t_f)$$
$$\delta_{cell} \le t_f$$

Material Properties Constraints

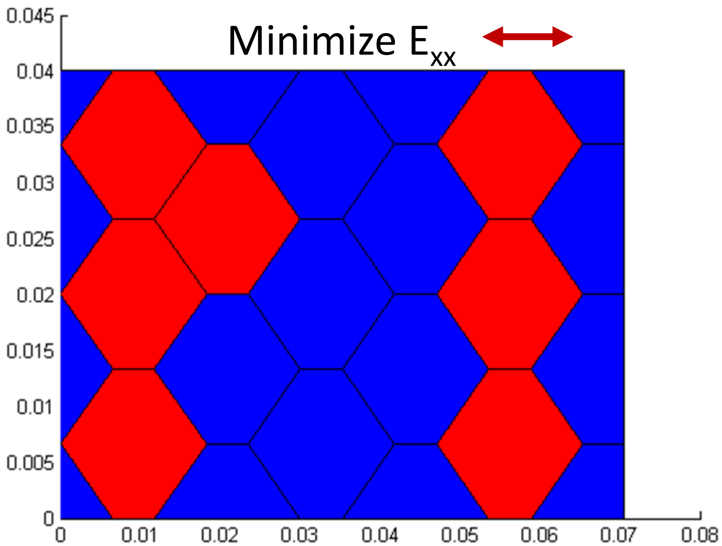
$$\frac{C_1 w b_{panel}^2}{t_f h_{core}} = \sigma_{max} \le \frac{1.0E7\,(Pa)}{2} = \frac{\sigma_f}{FOS}$$
$$\varepsilon_{x\max} \le \varepsilon_{xf} = \frac{l(\cos(\beta_x) - \cos(\theta))}{a + l\cos(\theta)}$$
$$\beta_x = \cos^{-1}\left[\frac{\varepsilon_{if}a}{l} + \cos(\theta)(\varepsilon_{if}+1)\right]$$
$$\varepsilon_{y\max} \le \varepsilon_{yf} = \frac{\sin(\beta_y) - \sin(\theta)}{\sin(\theta)}$$
$$\beta_y = \cos^{-1}[\sin(\theta)(\varepsilon_{if}+1)]$$
$$\varepsilon_{if} = 200\%$$

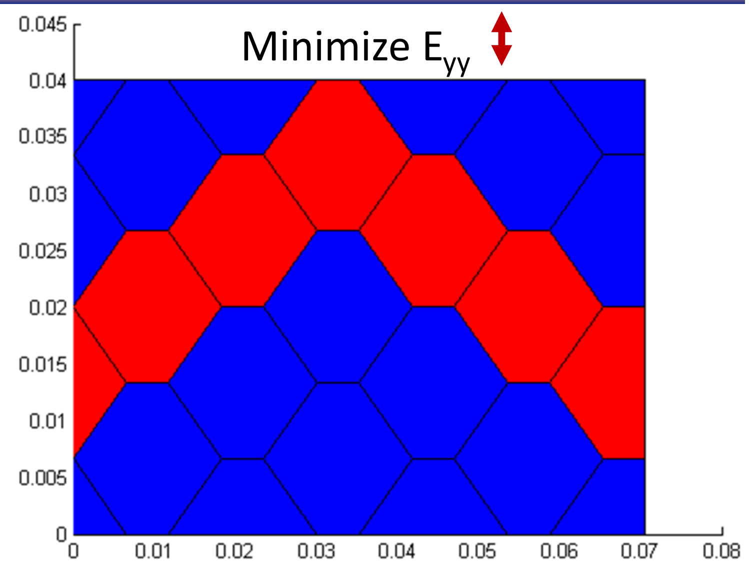


Optimized Geometry

l	10 mm
a	1.0 mm
d	0.05 mm
θ	62°
h_{core}	172 mm
t_f	2.5 mm

Heating Pattern Optimization

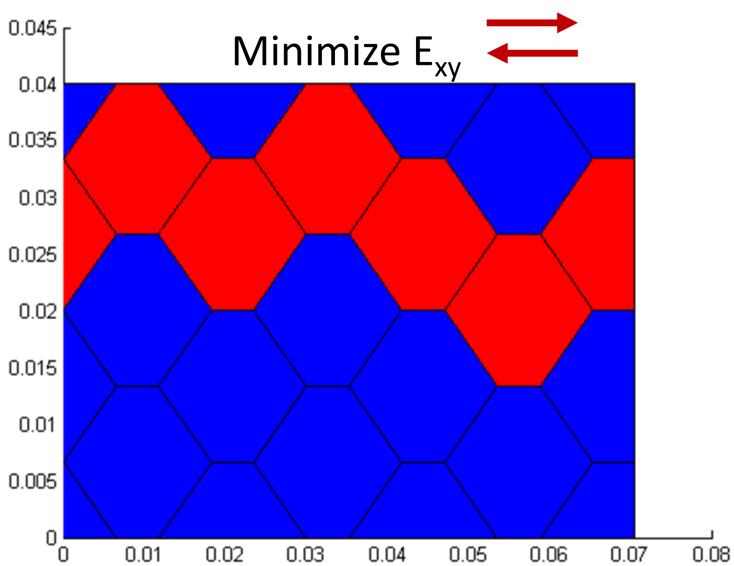


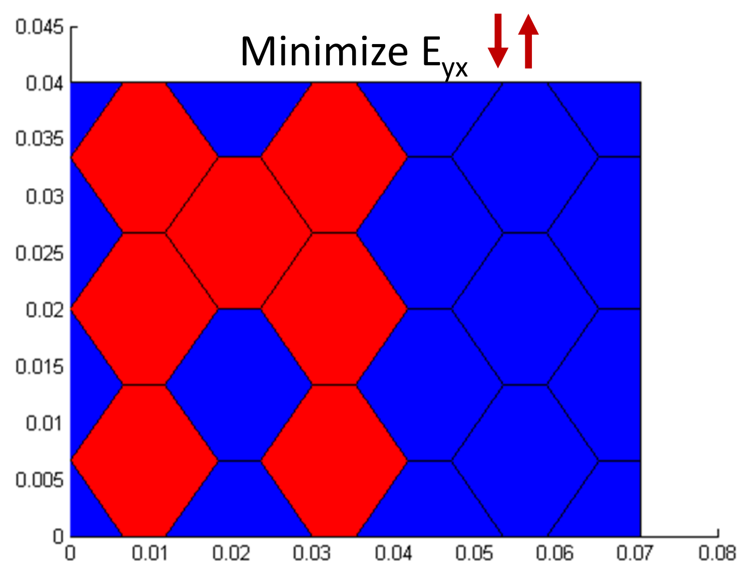


Genetic Algorithm

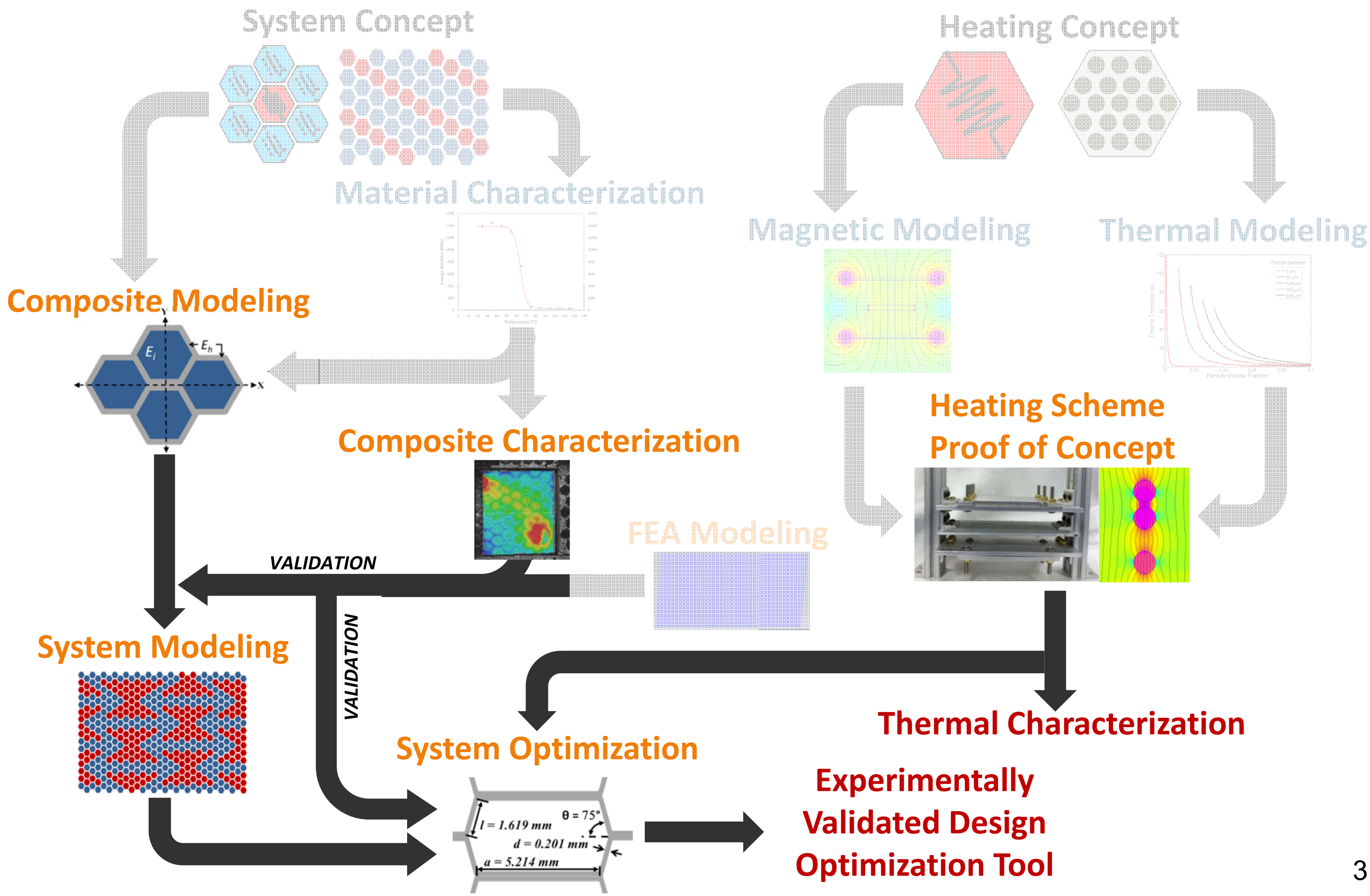
13 full cells
12 partial cells
7 hot cells
18 cold cells

Not included:
Out-of-plane def.
Deformation req.





Project Roadmap



Future Work

Future Work System Scheme

- Heating Pattern Optimization
- System Integration / Fabrication
- System Characteristics Envelope

Future Work Heating Scheme

- Thermal characterization of heating scheme
- Thermal diffusion between cells
- Direct write electrodes (variable patterns)

Conclusions

Conclusions

- **Viable Option for Morphing Structures**
- **30-40% In-plane Strain Achievable**
- **Accurate Analytic Model of Filled Honeycomb**
- **Optimistic High Thickness SMP Heating Scheme**